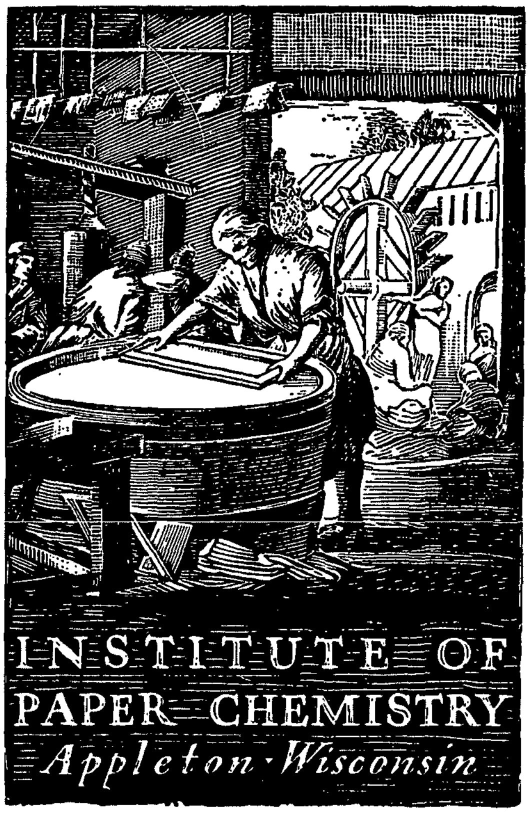

MECHANICS OF FLUTING

Project 3396

Report One

A Progress Report

to

MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

June 15, 1981

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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SUMMARY

The overall objective of this research is to develop basic information on the fluting process to optimize board strength and maintain runnability. This is the first phase of a continuing project concerned with the corrugating process. In this work we have directed attention to both the cold (room temperature) and hot fluting processes in relation to their effects on the strength of the medium. The strength of the medium after forming affects such combined board qualities as edgewise compressive test strength (ECT) and flat crush load-deflection behavior.

Our results indicate that the flat crush and ECT potentials of corrugated board which are dependent on the medium are greatly reduced by the fluting process. This occurs because fluting causes large reductions in the edgewise compressive strength and other properties of the medium under both hot and cold forming conditions. The compressive strength of the fluted medium correlates well with the flat crush strength of the combined board. The reductions in strength are caused by the high bending and tension stresses induced in the medium during fluting. Improved understanding of the fluting process may provide the basis for improvements in corrugating.

For some mediums the strength reductions are more severe under cold fluting conditions. This reduces the ultimate flat crush strength. However, we found that the initial flat crush load-deflection behavior is the same for both cold and hot fluting, only the failure loads are different.

Future work will be directed to determining ways to improve the performance of medium in the fluting process. This will involve consideration of corrugator operation, design, and the properties of the medium.

INTRODUCTION

The corrugating process is the basic step in the manufacture of corrugated containers. Corrugating performance depends on the (1) machine design and operating conditions, (2) properties of the medium and linerboard and (3) characteristics of the adhesive. The economics of the industry is vitally affected by the efficiency of the corrugating process.

In its simplest concept, corrugating is a forming operation. The medium is drawn under tension into the nip between the corrugating rolls, termed the labyrinth. In the labyrinth the medium is bent to the flute contour under the prevailing stress, temperature, and moisture conditions. At the center of the labyrinth high transverse compressive forces are applied to the medium which serve to "set" the fluted shape. Thus high tensile, compressive and shear stresses are induced in the medium as it is formed. These stresses affect combined board quality and can cause flute fracture or excessive high-lows during the corrugating operation.

Historically corrugating has been carried out with the corrugating rolls heated to high temperatures of about 350°F. The high temperatures were believed to be necessary for proper flute formation at high speeds. They also serve to "set" the adhesive.

However, our work has shown that commerical mediums can be corrugated satisfactorily under "cold" conditions, i.e., with the corrugating rolls at room temperature. The cold process reduces both energy and capital requirements.

Most of the properties of the cold formed board are comparable to those of hot formed board. However, we have found that some mediums exhibit lower flat crush strength when cold formed although the initial portions of the load-deflection curves are comparable.

Accordingly, the overall objective of this research is to analyze the corrugating forming process to determine the characteristics which optimize the structural performance of the board and maintain runnability under hot and cold forming conditions. Initial emphasis was placed on determining how medium and board performance is affected by cold and hot fluting. However, our results show that the differences between fluted and unfluted medium are more important than the differences between hot and cold fluting.

In this first phase of a continuing project we have directed attention to the effects of forming conditions, forming geometry and flat crush behavior.

BACKGROUND

In general, corrugating performance under either cold or hot fluting conditions is limited by several factors which affect board quality. They include flute fractures, high-lows and adhesion. For example, fractured flutes lower the quality of the board as noted by McKee and Gander (1). They reported losses in flat crush ranging up to 13% and losses in edgewise compressive strength of up to 20%. Usually the strength falls off gradually with increasing speed because only sporadic fractures are initially encountered as noted by Gottsching and Otto (2). However, the presence of fractures is usually marked by an increase in flat crush variability. Thus the corrugating process imposes high stresses in the medium which can lower board quality if they exceed the "strength" of the medium. Even though fracture does not occur, the stresses during fluting reduce the strength of the fluted medium. These effects of the fluting stresses are the subject of this work.

FORMING STRESSES

At the entrance to the labyrinth (See Fig. 1) the main stress on the medium is due to the applied brake tension. The tensile stress at A is approximately constant across the medium thickness. The web tension in the medium is one of the most important factors affecting runnability and board quality. Many investigators have shown that increasing web tension causes fracturing at lower speed (1-4).

In the labyrinth (Regions A to C, Fig. 1) the medium must travel faster than the tips on the corrugating rolls to accommodate the take-up or draw. As a result there is a frictional drag on the medium. The drag progressively increases the web tension as the medium is formed to the contour. McKee and Gander (1,5) showed that the web tension near the center of the labyrinth is much greater than the initial or brake tension. Figure 2 shows that the web tension in the final stages of forming is strongly dependent on the coefficient of friction, μ, between the medium and the corrugating rolls. Recently, Thomas (6) obtained similar results in an analysis of the C-flute labyrinth (Fig. 3).

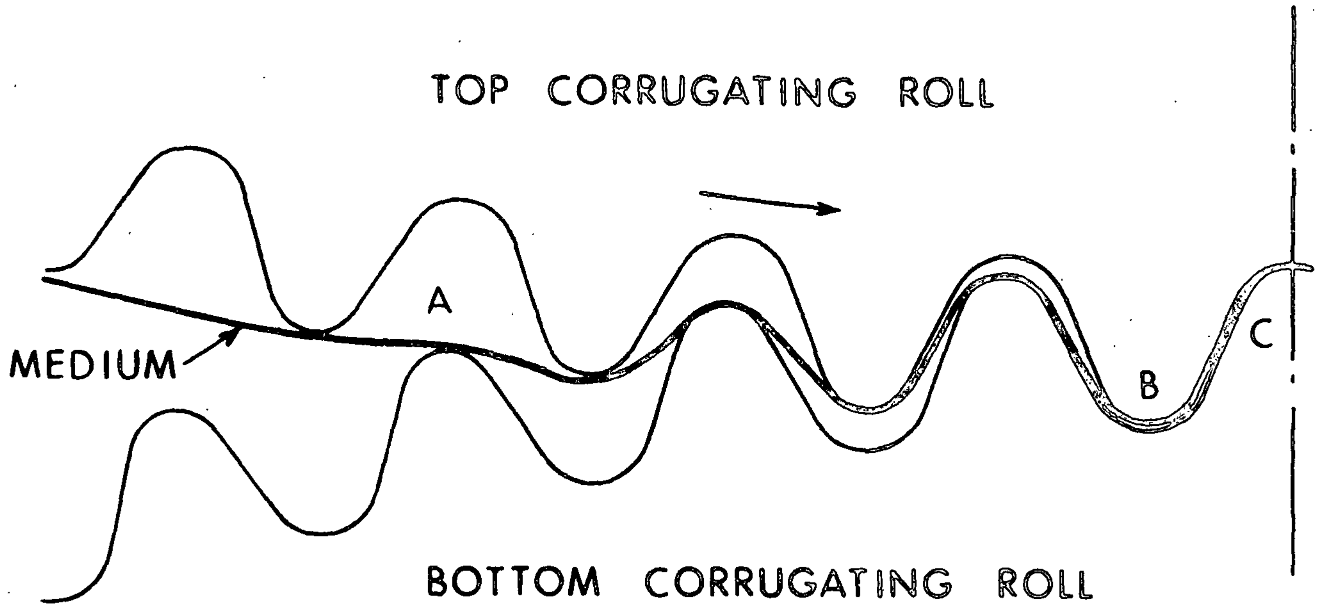

Figure 1. Corrugating Labyrinth

Figure 3 shows that increasing the coefficient of friction between the medium and corrugating roll surfaces from 0.2 to 0.3 will cause a 100% or more increase in the final tension in the medium. For this reason the application of a small amount of certain "slip" agents to the medium or corrugating roll will reduce the tension in the medium during forming. Markedly higher corrugating speeds can be achieved using such agents. The effectiveness of various agents under "hot" corrugating conditions is discussed in Ref. 7. "Slip" agents also reduce the tendency to form high lows (7, 8).

Under cold corrugating conditions we have found that many mediums must be treated with friction reducing agents to prevent fracture and minimize high-lows (9-11). The coefficient of friction of corrugating medium is often much higher at

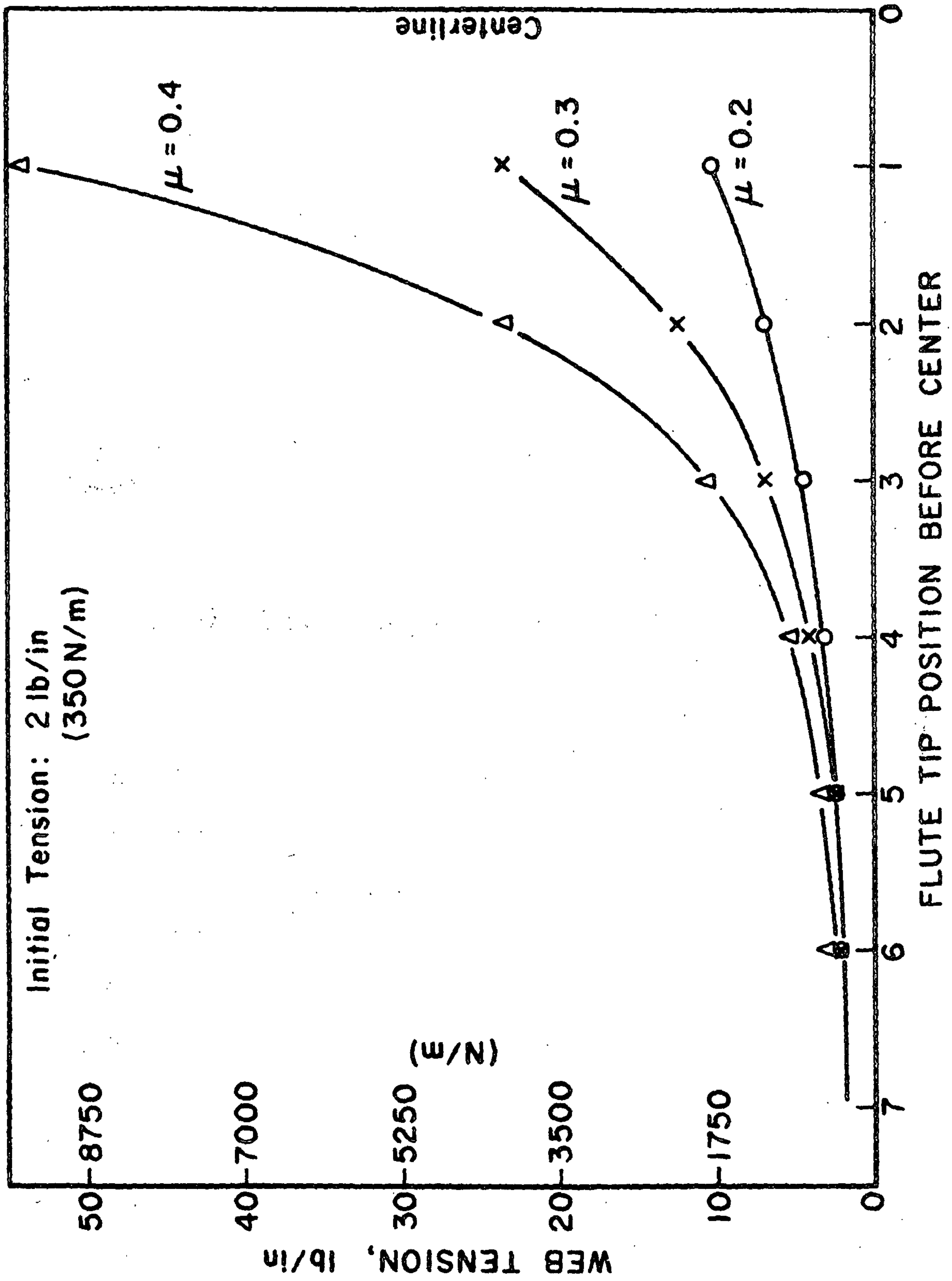

Figure 2. Effect of Friction on Web Tensions in the Corrugating Labyrinth (μ = Coefficient of Friction) [From Ref. (5)]

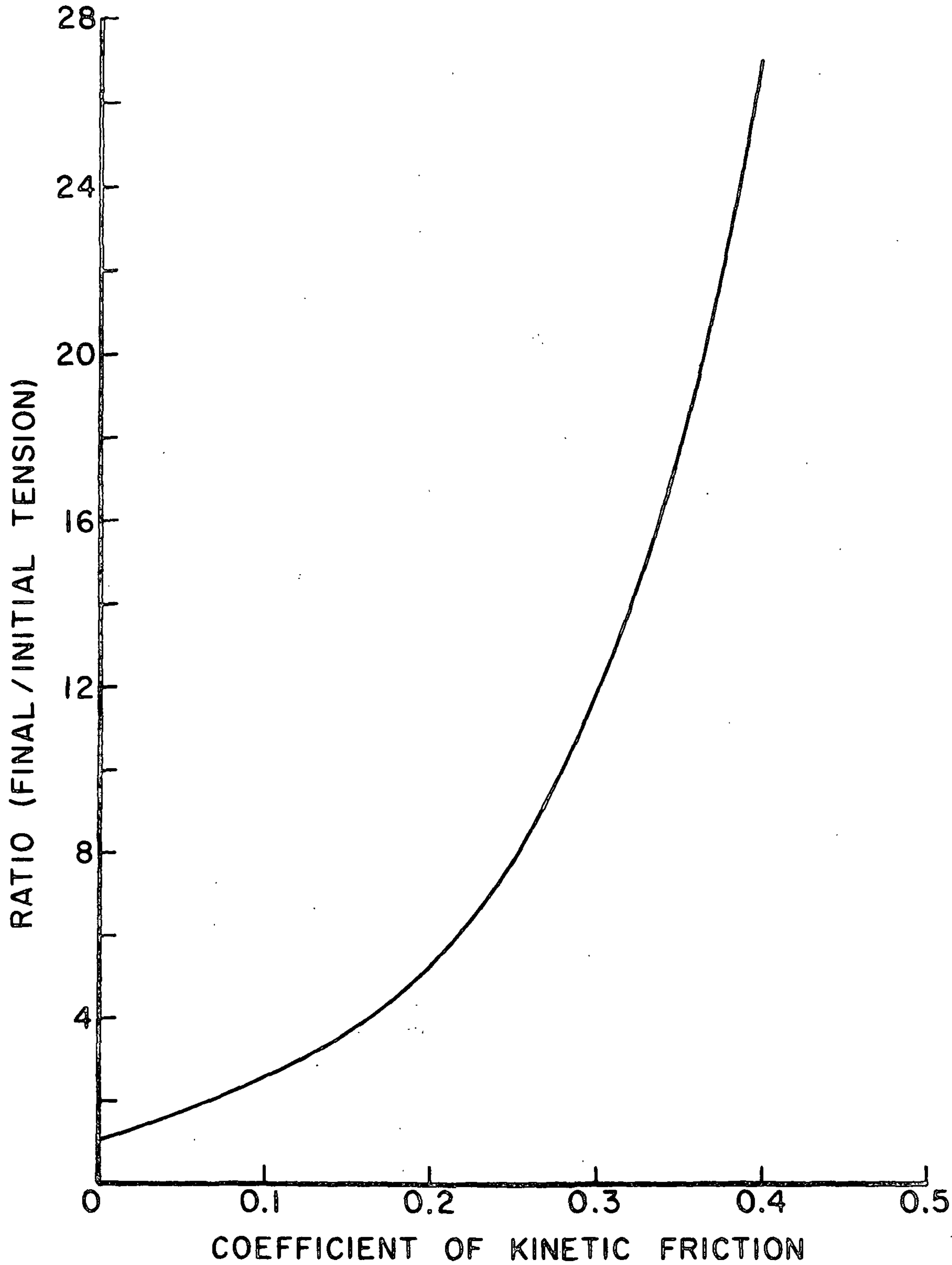

Figure 3. Maximum Web Tension in Labyrinth for a C-Flute Contour [after Ref. (6)]

room temperature than under hot corrugating conditions. In such cases flute fracture will occur unless suitable agents are used. Our results indicate that the effectiveness of various slip agents varies with the corrugating temperature condition (9).

The medium at the flute tips is bent to the tooth radius giving rise to tensile stresses on the outside and compressive stresses on the inside (Fig. 4B). When added to the transport tensions (Fig. 4A), the stress on the outside convex surface is increased as illustrated in Fig. 4C. A critical state of stress may be reached when the transport and bending stresses are added and hence cause tip fracture. The bending stresses and strains will depend on the medium caliper and radius of curvature of the corrugating roll flute tip. The higher the caliper or the smaller the radius, the greater the strain and hence likelihood of fracture.

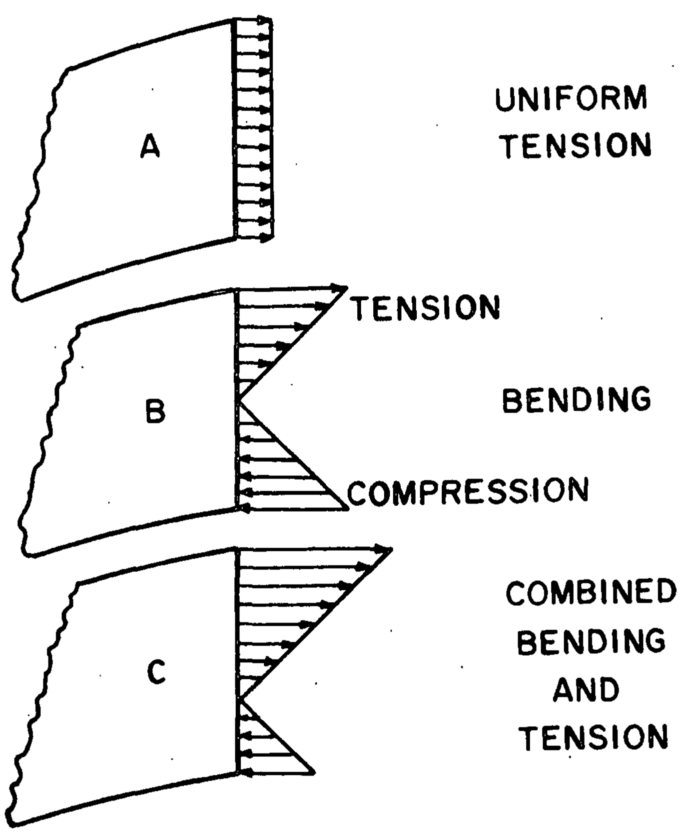

Figure 4. Combined Bending and Web (Uniform) Tension [Ref. (1)]

Estimates of bending strain on the flute tip are greater than the allowable machine direction stretch of medium (1,6). Shear stresses induced in the medium reduce the net bending strain to permit forming without fracture. The transverse shear modulus of medium is quite low compared to the in-plane moduli. This is due to the "layered" nature of most paperboards. The shear strains generated in the medium will reduce the intensity of the bending strains and assist in the forming. As an extreme example some mediums delaminate during corrugating due to excessively high shear strains.

At the center of the labyrinth, point C in Fig. 1, high transverse compressive forces are applied to the medium. The medium thickness in the tip and root regions is reduced which helps "set" the flute contour (1). Greater caliper reductions are obtained under hot corrugating conditions than cold conditions.

The web tension and transverse compressive stresses oscillate in magnitude during the formation of each flute due to the up- and down- motion of the top corrugating roll (12-14) and possible draw variations in the labyrinth. Figure 5 illustrates the oscillatory nature of the web tension, top corrugating roll pressure and "up-and-down" corrugating roll acceleration (14). The fundamental frequency of the oscillating forces is the flute forming frequency but large higher harmonics are usually present. The variations in web tension are particularly important because they will be magnified in the labyrinth. Substantial increases in web tension could occur as a result.

Briefly summarizing, the medium is exposed to tension, bending, shear, and transverse compressive stresses in the forming operation. The stresses are high enough to bring about changes in the fiber-to-fiber bonding of the medium and, hence, affect board quality. If the induced stresses in the medium are too high under the

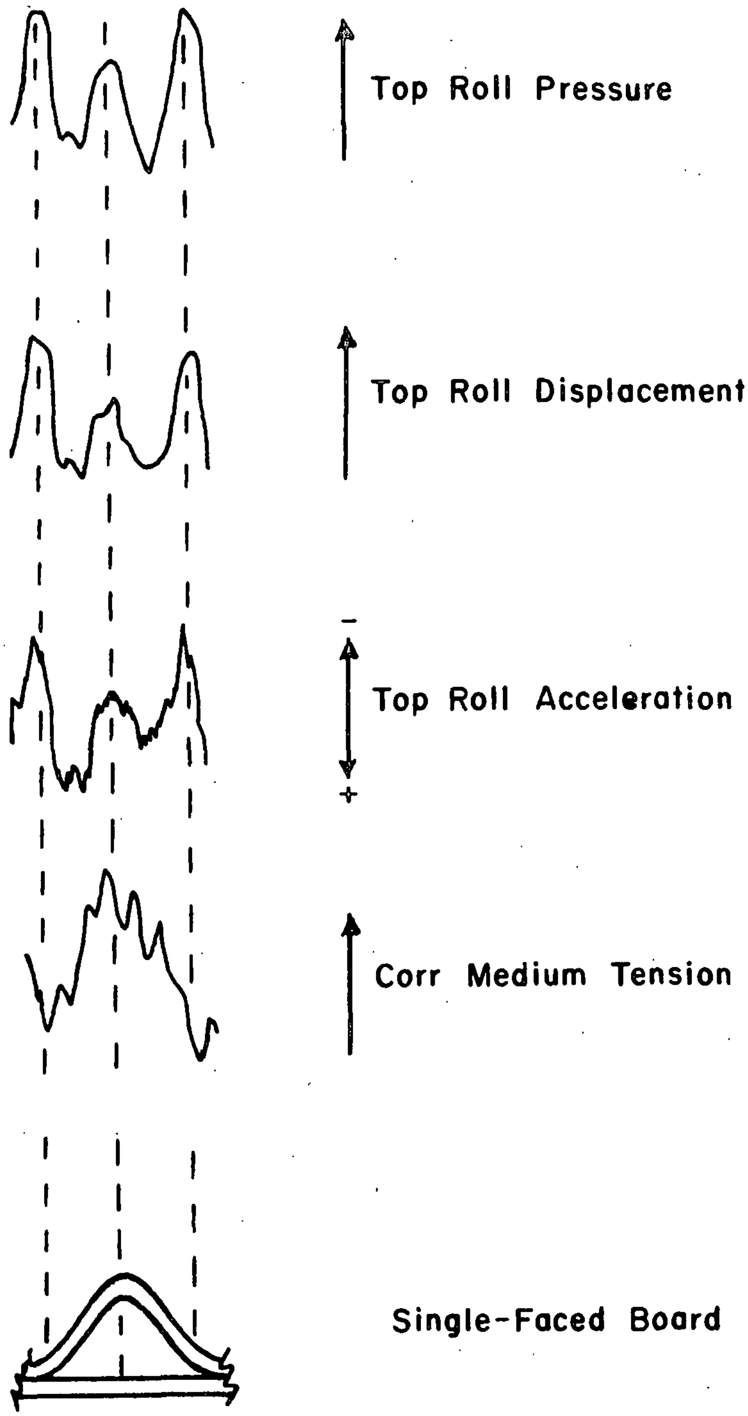

Figure 5. Oscillatory Nature of Corrugating Forces and Corrugating Roll Displacement [Ref. (14)]

prevailing conditions of heat, moisture and rate of stressing, severe high-lows and fracturing of the medium will occur. Lower stress levels avoid these visually evident defects but may still damage the medium to severely reduce strength potentials.

TEMPERATURE AND MOISTURE EFFECTS IN CORRUGATING

Various authors have emphasized the importance of corrugating temperature on both flute fracturing and high lows (see Ref. 2-4, 15-17). It is believed that the lignin and hemicellulose components in the medium become more plastic and "flow" at high corrugating temperature, particularly if somewhat moist. The "flow" of these components is believed to assist the medium in forming to the flute contour and in retaining its flute shape so as to minimize high-low flute formation. This hypothesis explains many of the phenomena observed in normal corrugating with hot (350°F) corrugating rolls. However, we have shown that corrugating can be carried out under room temperature conditions where thermal softening effects do not occur. It also may be remarked that the new fingerless corrugators have reduced high-low problems (18-20) under hot conditions and presumably will do so under cold conditions.

COLD *vs*. HOT CORRUGATING FLAT CRUSH

Most commercial mediums can be corrugated satisfactorily under cold conditions. In general, the properties of the cold formed board are about the same or better than obtained under hot corrugating conditions. However, cold formed board made with some mediums exhibits lower ultimate flat crush strength than hot formed board. While the ultimate flat crush strengths may differ, the initial portions of the load-deflection curves are comparable for cold and hot formed board (Fig. 6). The first peak strengths are approximately equal for all commercial mediums evaluated to date. Thus, cold and hot formed board should show about the same response when subjected to low degrees of crushing by pull rolls and belts.

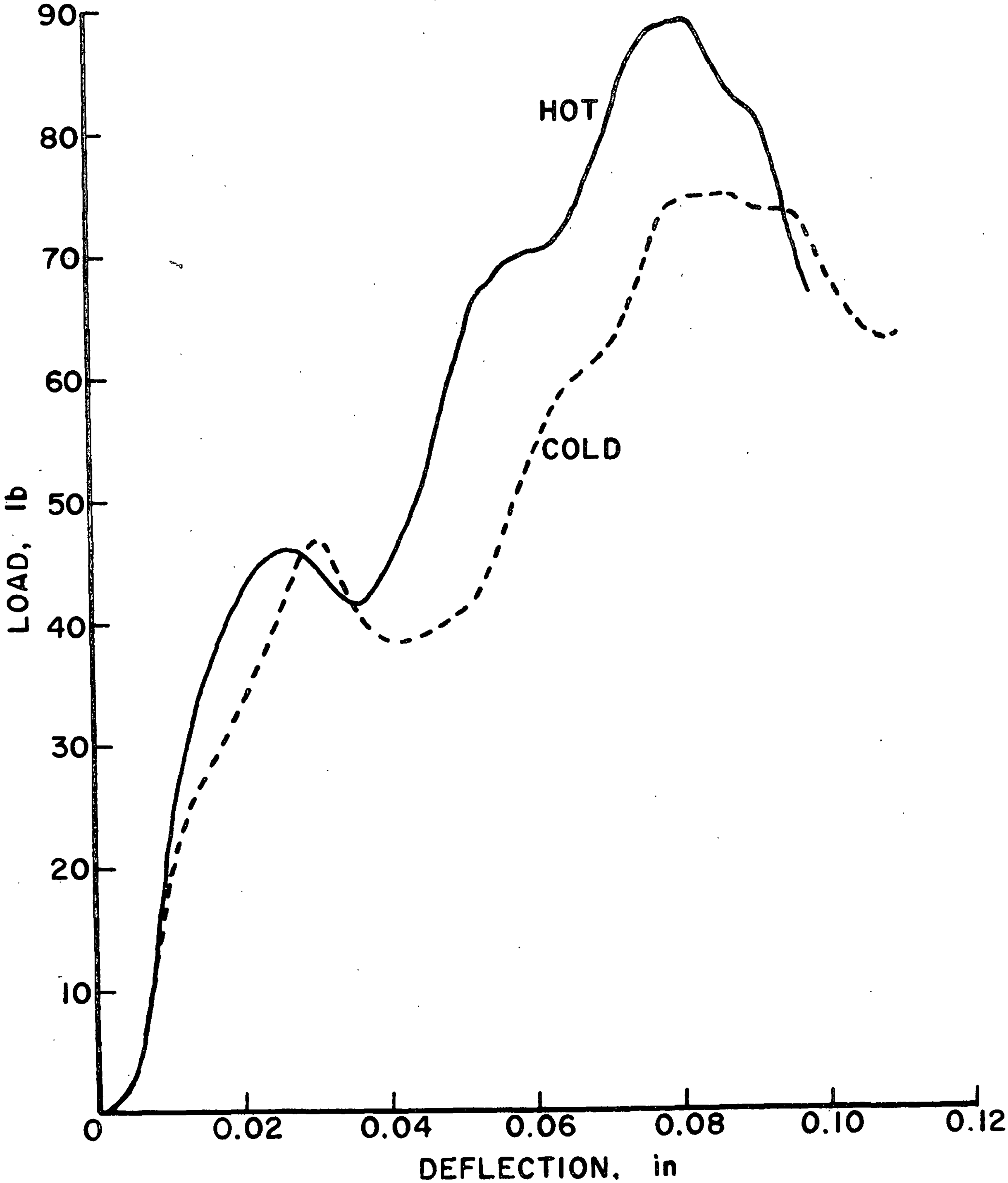

Figure 6. Typical Flat Crush Load-Deflection Curves for Cold and Hot Formed C-Flute Board

When combined board is crushed between rigid steel rolls, all boards will suffer the same amount of caliper reduction. Medium stiffness and weight will have no effect on the degree of caliper reduction and degradation in other properties dependent on the effective caliper. Most of the literature discusses roller crushing effects.

On the other hand, if boards are subjected to the same transverse stress, boards with stiffer mediums will crush less than boards with weaker mediums. Thus, for a given load, the board with stiffer, heavier medium should exhibit less degradation in board properties. This stressing process is more likely to occur in transportation, e.g., humping operations.

Early work at the Institute was concerned with the effect of crushing on combined board properties and the flat crush fatigue behavior of combined board (21,22). The shape of the flat crush load-deformation curve was discussed (22), and it was pointed out that loads greater than the first peak caused significant nonrecoverable deformation, i.e., degradation of the combined board. It was also shown that combined board can withstand many repeated transverse loadings if the applied loads are kept below the first peak load.

In more recent work, Staigle (23), Crisp, et al. (24), and Nordman, et al. (25) discussed the crushing of combined board in the converting process by feed rolls and belts. Staigle (23) showed that the permanent loss in caliper as measured using the TAPPI procedure is much less than the actual caliper reduction when board is passed between steel rolls. Thus, a permanent caliper loss of 10 mils may result from a roll crush treatment of 40 mils. In Fig. 6, a 40 mil reduction in caliper would cause nonreversible deformations and degradation of board properties would be expected even though the permanent caliper loss is much less than 40 mils. Crisp (24) also crushed board between rollers and evaluated the changes in board properties. He defined "hardness" as the greatest flat crush load up to 0.010 inch deflection and concluded hardness was more sensitive to board damage than caliper. Thus, the early portion of the flat crush curve was considered to be more important insofar as box plant crushing is concerned, although hardness decreased much more than box compression. The flat crush test was not suitable as a damage indicator because the maximum flat crush load was not affected by small amounts of crushing.

Nordman, et al. (25) studied crushing of combined board between steel rolls and confirmed Staigle's work on caliper recovery. The major portion of the reduction in thickness due to roller crushing is recovered. However, the effective structural thickness has actually decreased because the fluted medium is damaged. Thus board properties dependent on the effective thickness are reduced. Both Crisp and Nordman found that flexural stiffness, caliper, first peak flat crush load, and box compression decrease with increasing degrees of crush, particularly as the flat crush first peak deformation is exceeded. However, the decreases in box compression strength do not necessarily accelerate until extreme degrees of crush are imposed.

Morris (26) has emphasized that satisfactory container performance during transportation is important. In transportation, the loaded box must cope with repeated applications of stress at low to high levels. He contends that medium stiffness is an important factor in maintaining box compression performance potentials through the transportation environment. He believes the field box continues to function until we crush the legs of the flute, i.e., flat crush test failure. This contention is probably consistent with the box results after crushing which were obtained by Crisp and Nordman (24,25). As a final comment, the results in Ref. (28) show that precrushing board to given stress levels causes reductions in box compression which vary with medium stiffness as well as flute and other factors.

Briefly summarizing, it appears that

(1) The initial portion of the flat crush load-deflection curve is more critical than ultimate flat crush in assessing whether a given degree of crushing will degrade board quality.

(2) The entire load-deflection curve is important to box performance because boxes can continue to function even though the crushing has exceeded the first peak deflection.

DISCUSSION OF RESULTS

For our initial work, we focussed attention on the m.d. and c.d. edgewise compressive characteristics of the medium as related to forming conditions. The compressive characteristics of the medium affect the converting performance of combined board and end-use box performance. The medium contributes directly to c.d. short column strength (along with the liners) and indirectly to flexural stiffness where it serves primarily to maintain the desired liner separation. The latter involves the flat crush load-deformation characteristics of the formed medium and, hence, the m.d. edgewise compressive properties of the medium. Crushed combined board, whether in converting or end-use, is a weak product. Thus the compressive characteristics of the medium in both directions are involved in box performance.

Accordingly we planned and carried out work in the following areas:

1. Evaluation of the effect of hot and cold forming conditions on the compressive characteristics of the medium. Other properties such as tensile and bonding strength were also considered.
2. Effect of forming conditions on flute shape
3. Relation of flat crush to medium properties - structural models.

FORMING CONDITIONS vs. MEDIUM PROPERTIES

Most of our work was carried out using four commercial 26 lb mediums. There were three semichemical mediums and one recycled fiber medium. As expected, the recycled fiber medium contained a higher percentage of long softwood fiber than the semichemical mediums. Two of the mediums exhibited about equal flat crush under cold and hot corrugating conditions; the other two mediums exhibited lower cold than hot flat crush. The physical characteristics of the mediums are summarized in Appendix I together with the general procedures employed.

To determine the degree of change in the edgewise compressive characteristics of formed medium, we made short span compressive tests on fluted but unbonded sections of cold and hot formed medium. The compressive tests were made on the STFI strip compressive tester which employs a test span of 0.7 mm (28). The short test span permits localized strength determinations which are of great value in studying formed flutes.

The machine direction STFI compressive results taken at various positions around the flute are shown in Fig. 7 and 8 for the "different" and "equal" cold/hot flat crush mediums, respectively. The results show that the formed medium exhibits much lower compressive strengths than the uncorrugated medium. This is true for both hot and cold formed medium although there are some significant differences which are noted below. Overall the reductions in m.d. compressive strength were about 42%. We believe the reductions in compressive strength reflect fiber bonding damage caused by the high stresses in the forming process.

The m.d. compressive strengths in the flank and tip/flank regions (positions 2-4 and 6-8) tended to be somewhat lower on the cold formed medium than the hot formed medium in Fig. 7. This was more evident on the trailing flank. As mentioned, the two mediums in Fig. 7 exhibited lower cold than flat crush. In the case of the mediums where the cold and hot flat crush results were comparable, the compressive strengths of the hot and cold formed mediums were about the same (Fig. 8).

Figure 9 shows that the STFI compressive strengths in the tip/flank region are well related to flat crush for both the hot and cold formed boards. In contrast, the STFI compressive results on the uncorrugated medium were not well related to the flat crush results on the cold-formed medium. This helps confirm that degradation of the m.d. edgewise compressive potentials of the medium due to forming is a factor in flat crush performance.

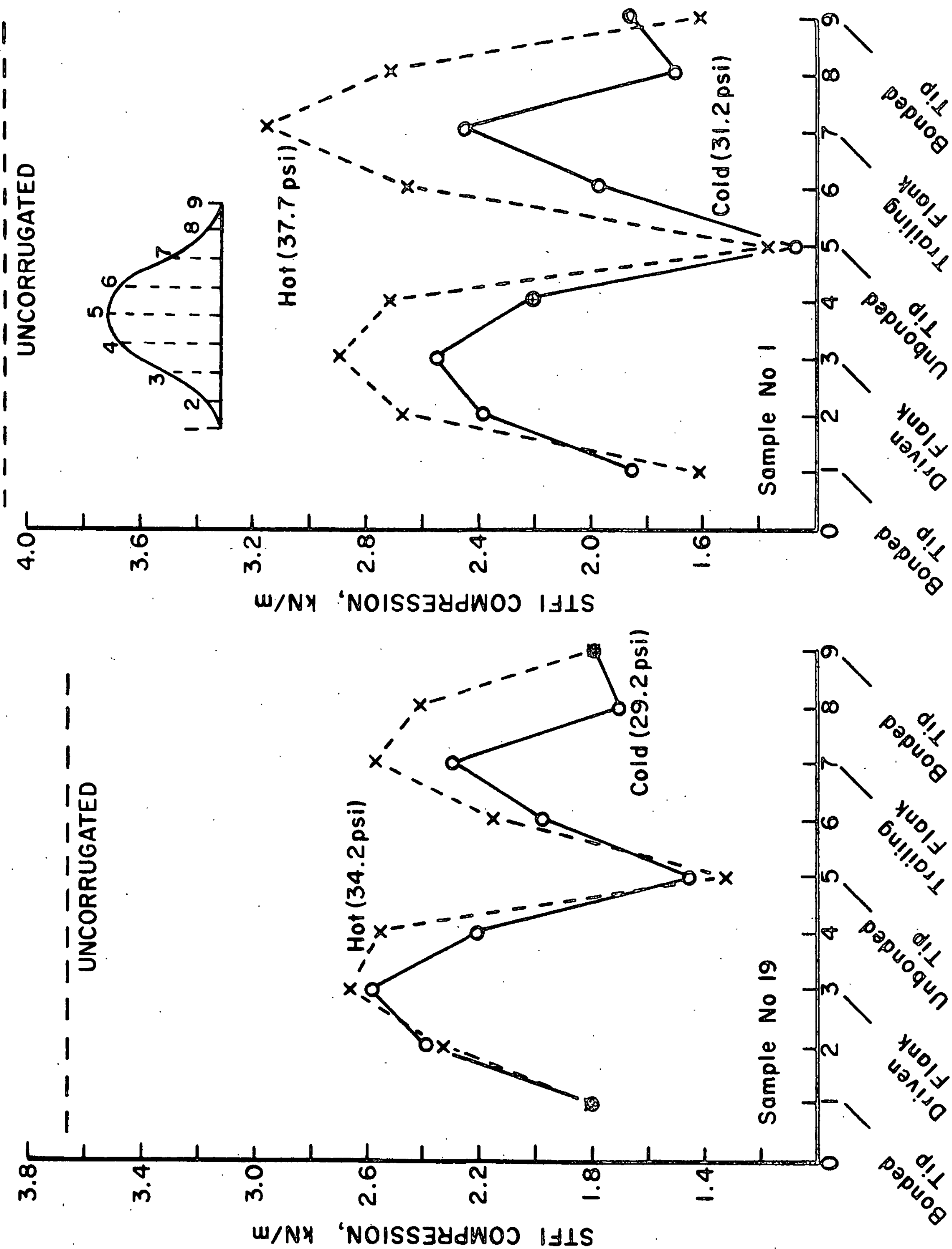

Figure 7. Machine Direction Compressive Strength after Fluting for Mediums Exhibiting "Different" Cold/Hot Flat Crush Strength (Flat Crush Values in Parenthesis)

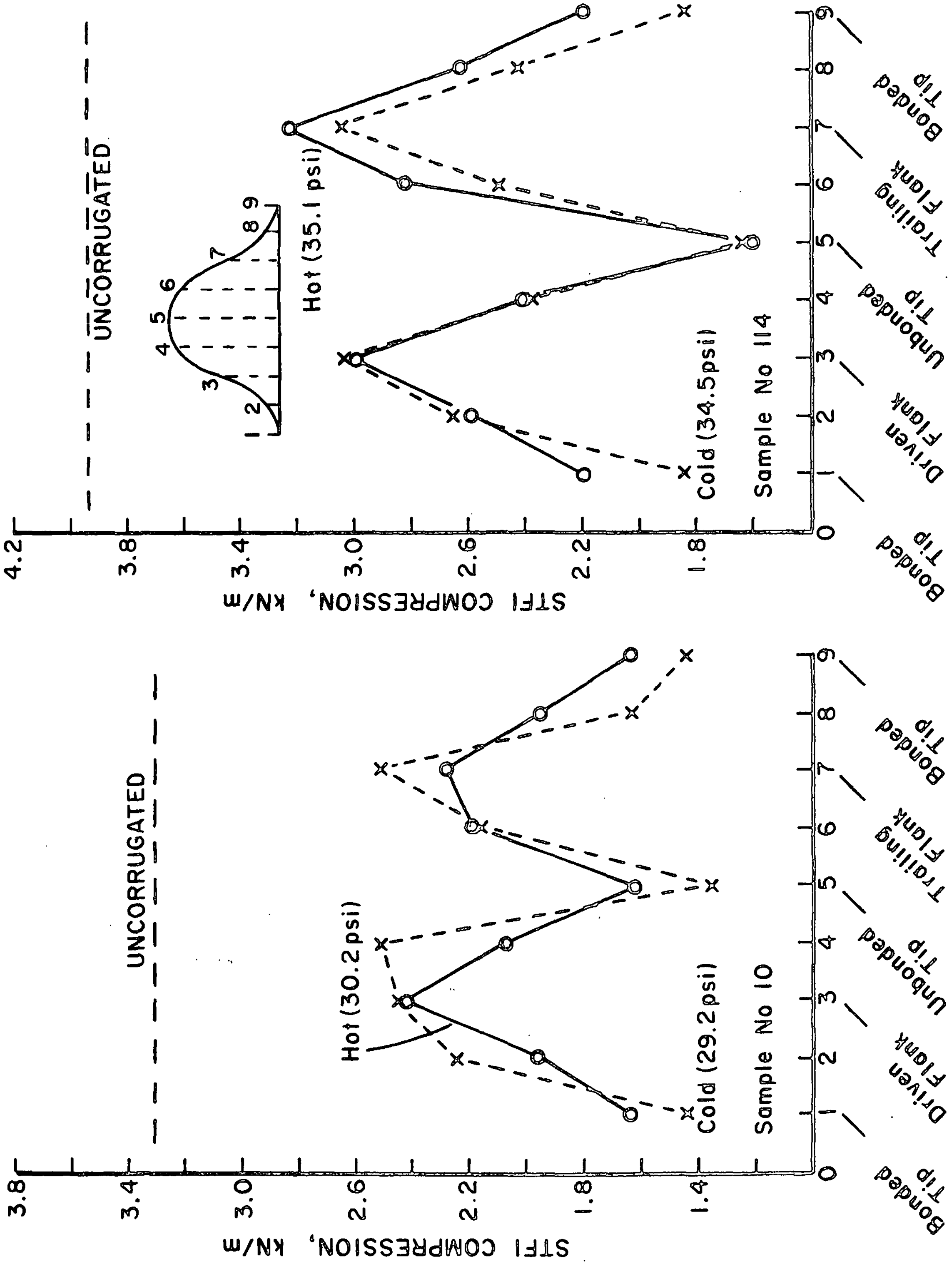

Figure 8. Machine Direction Compressive Strength after Fluting for Mediums Exhibiting "Equal" Cold/Hot Flat Crush Ratios (Flat Crush Values in Parenthesis)

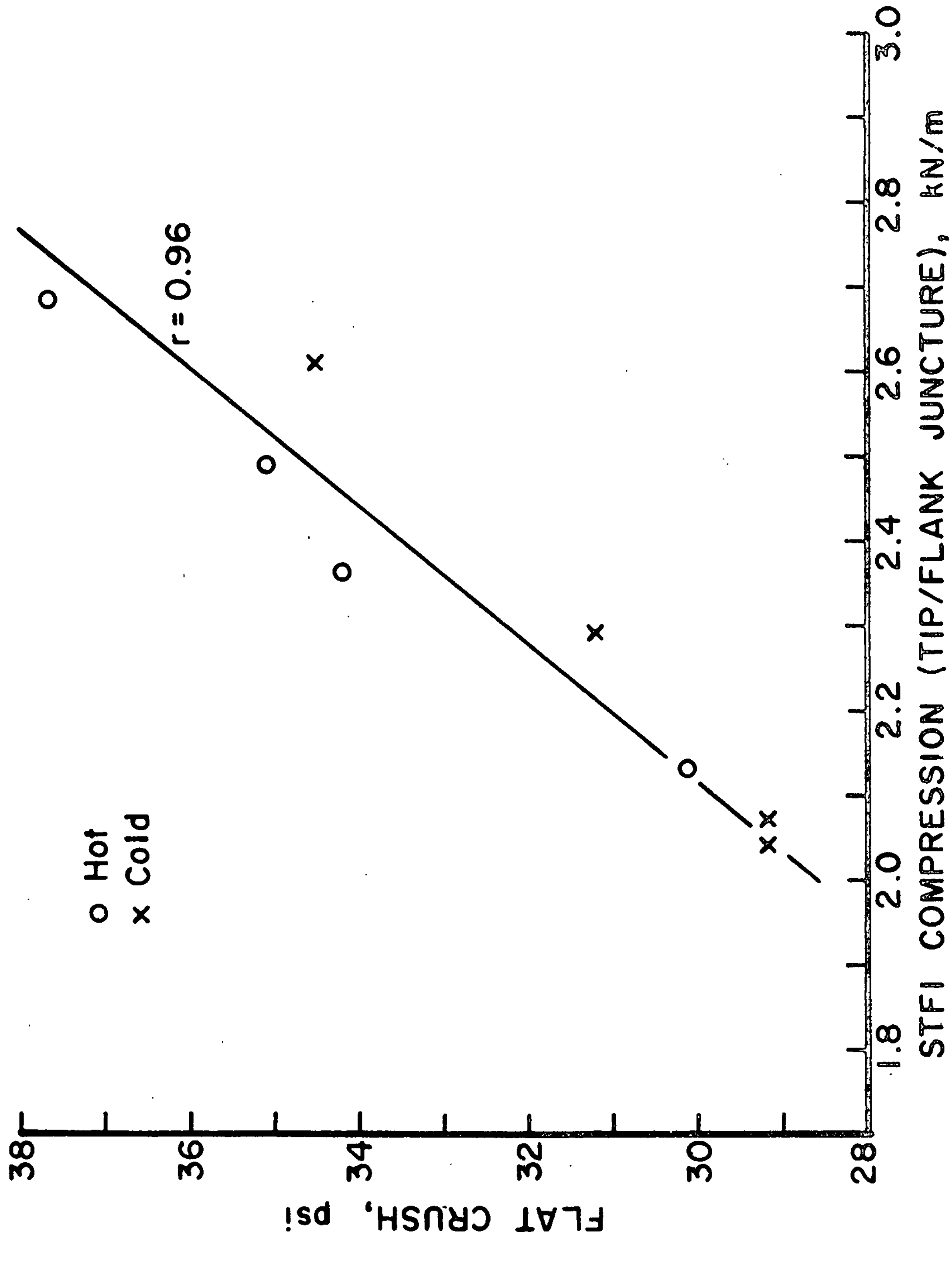

Figure 9. Relation Between Compressive Strength of the Fluted Medium and Flat Crush

When single-faced board is tested in flat crush the medium at the unbonded tip flattens and squares off as the first load peak is reached (see Fig. 10). Note that the cold formed board deformed less symmetrically and exhibits a broader flattened off portion. This would be expected if the compressive characteristics of the trailing flank were weakened more than the leading flank as occurred in Fig. 7. The flank/tip regions may be particularly critical because the "hinge" points are formed in these regions during the flat crush test.

At failure in flat crush the medium forms a hat shaped (frame) structure (see Fig. 11). The figure also illustrates that the cold-formed medium failed in a less symmetrical manner than the hot medium. In this example final failure appeared to be associated with the trailing flank for both forming conditions.

Based on observation and experiment, we believe it is reasonable to expect that the flat crush load-deformation characteristics should be related to the m.d. edgewise compressive properties of the formed medium. Thus the lower ultimate flat crush strength obtained with some mediums under cold conditions is a result of the greater compressive strength degradation in the flank/tip and flank regions of the flute.

Short span m.d. tensile tests on the formed medium showed reductions in strength ranging from about 17-44% compared to the uncorrugated medium on sample 1 (Table I and Fig. 12). In all cases the percentage reductions in tensile strength were less than in edgewise compressive strength, often much less. Thus, while forming affected both the tensile and compressive characteristics of the medium, compressive strength was more drastically lowered. We speculate this occurs because compressive strength is more sensitive to the delamination stresses which are induced in the forming process.

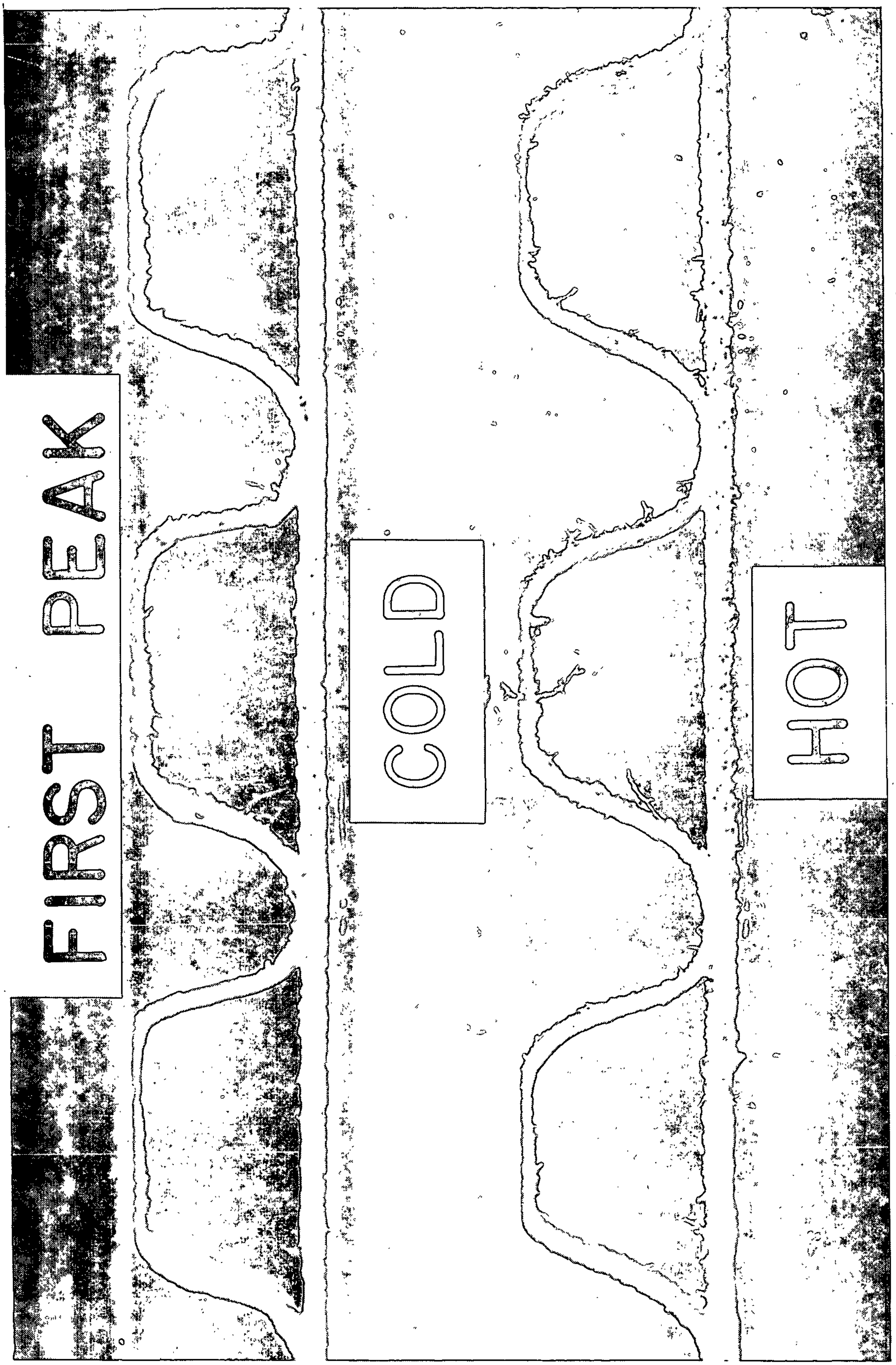

Figure 10. Appearance of Cold and Hot Formed Board at the First Flat Crush Peak (Trailing Flank to Right)

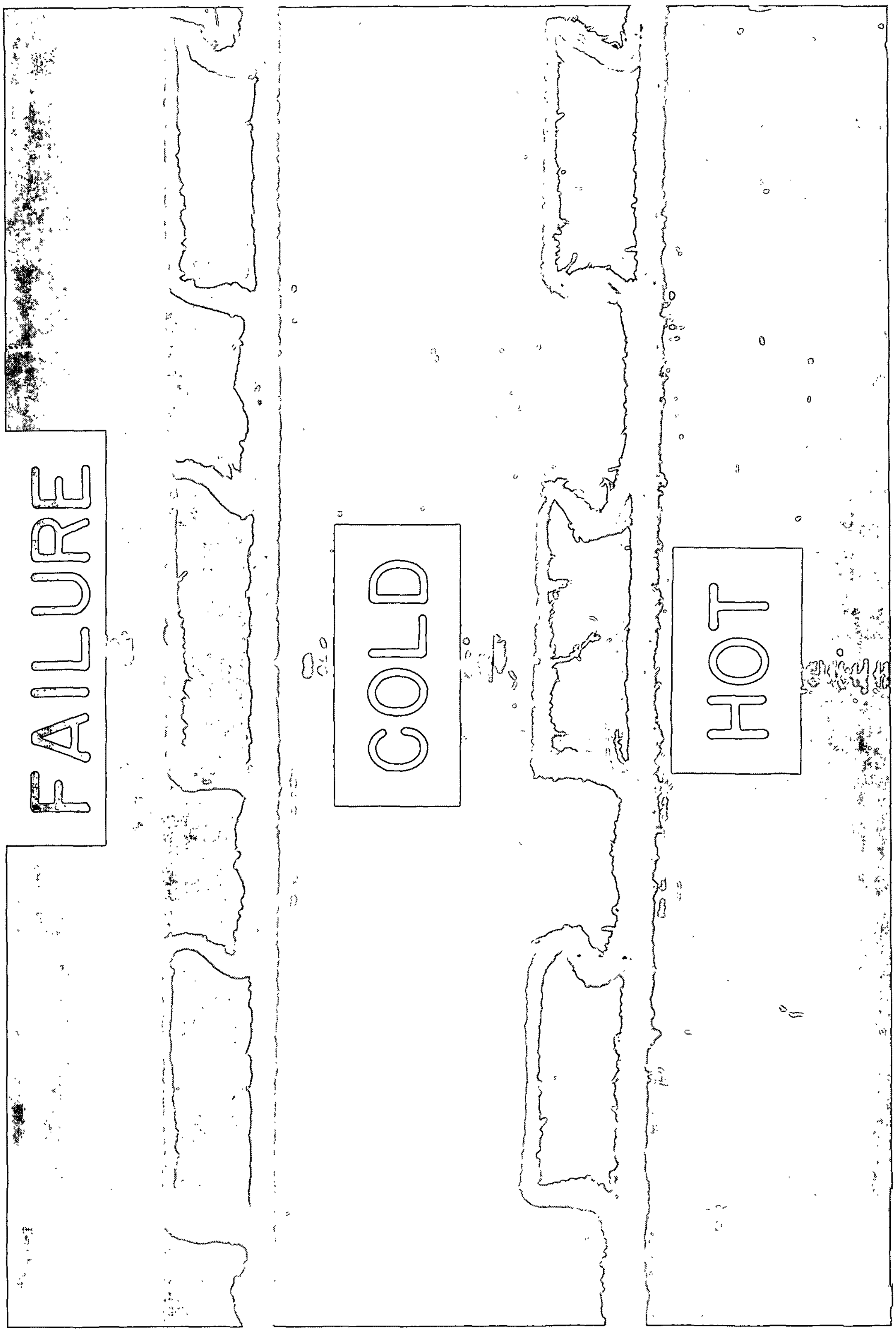

Figure 11. Appearance of Cold and Hot Formed Board at Flat Crush Failure (Trailing Flank to Right)

TABLE I

EFFECT OF FORMING ON THE LOCAL TENSILE AND COMPRESSIVE STRENGTH OF THE MEDIUM

(Medium Sample 1)

Flute Position	Forming Condition	Compressive Strength,[b] kN/m	Diff., %[a]	Short Span Tensile,[b] kN/m	Diff., %[a]
Uncorrugated	--	4.08	--	10.7	--
Corrugated					
Bonded root	Cold	1.86	-54.4	7.32	-31.6
	Hot	1.61	-60.5	7.65	-28.5
Root/driven flank	Cold	2.40	-41.2	6.58	-38.5
	Hot	2.67	-34.6	8.89	-16.9
Driven flank	Cold	2.55	-37.5	8.25	-22.9
	Hot	2.89	-29.2	7.62	-28.8
Unbonded tip/ driven flank	Cold	2.32	-43.1	6.63	-38.0
	Hot	2.71	-33.6	7.37	-31.1
Unbonded tip	Cold	1.28	-68.6	6.01	-43.8
	Hot	1.37	-66.4	8.65	-19.2
Unbonded tip/ trailing flank	Cold	2.11	-48.3	6.04	-43.6
	Hot	2.65	-35.0	8.35	-22.0
Trailing flank	Cold	2.45	-40.0	8.09	-24.4
	Hot	3.14	-23.0	8.05	-24.8
Bonded root/ trailing flank	Cold	1.86	-54.4	7.93	-25.9
	Hot	2.70	-33.8	8.30	-22.4

[a]Based on uncorrugated results as reference.
[b]STFI compressive and short span tensile spans were 0.7 and 1.27 mm, respectively.

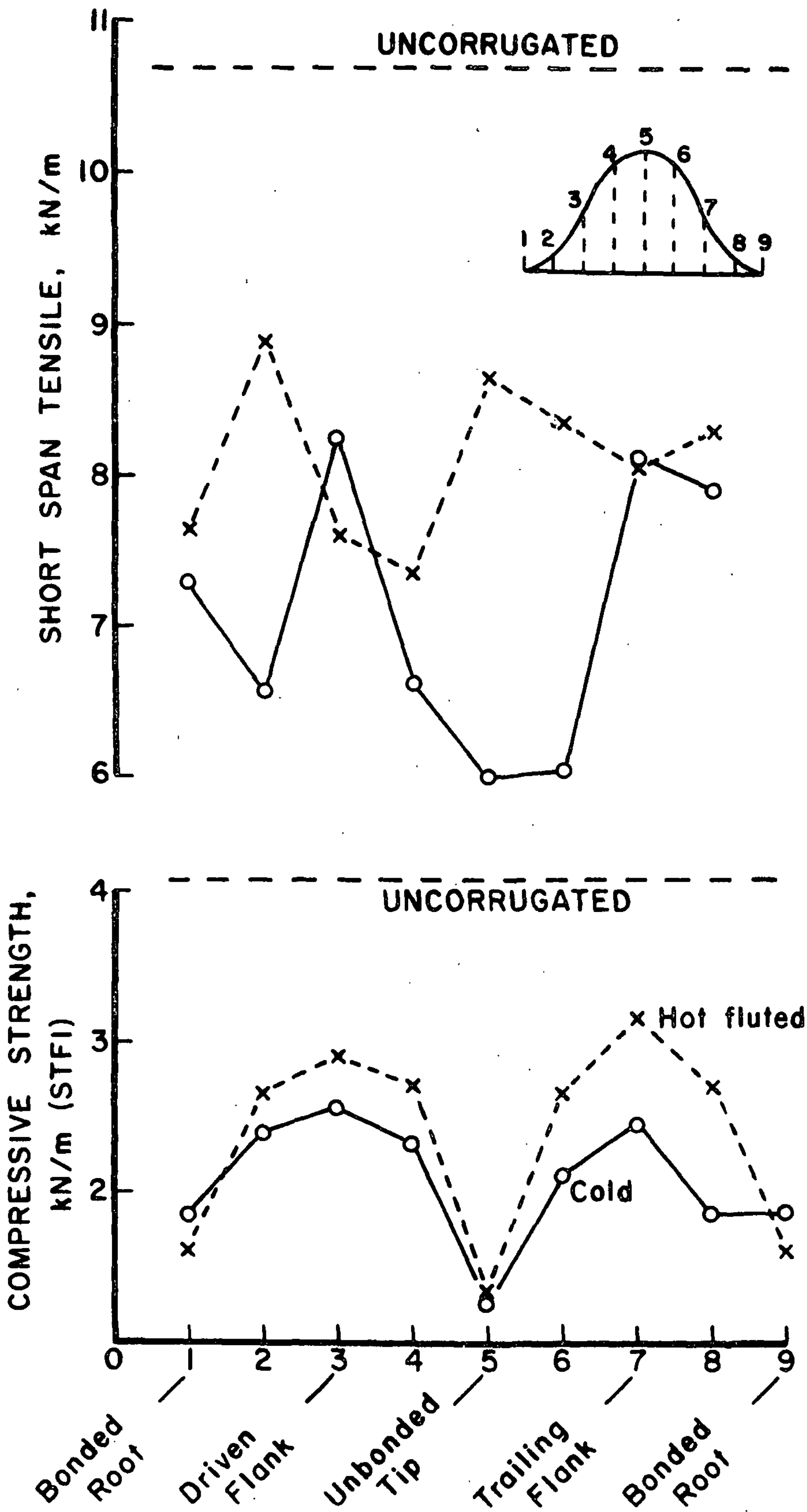

Figure 12. Effect of Forming on Short Span Tensile and Edgewise Compressive Strength of Sample 1

Figure 12 shows that the cold formed medium generally exhibits lower tensile strength than hot formed medium in all flute positions. However, the tensile strengths varied more erratically with flute position than compressive strength. In any case the reductions in tensile strength did not appear to be directly related to the cold-hot flat crush differences although they may affect other board qualities. This is not surprising because the flat crush load-deformation characteristics would be expected to be primarily dependent on the compressive characteristics of the medium.

We also carried out STFI edgewise compressive tests in the cross-machine direction on hot and cold formed medium. No separation by position on the flute was possible. Figure 13 indicates that forming reduces the edgewise compressive strength potentials of the medium in the cross direction. This is probably due to delamination induced by forming type shear stresses in forming as mentioned previously. The reductions are in the neighborhood of 20 to 30% and are not greatly different for hot and cold corrugating. Top load box compressive strength is dependent, in part, on the cross direction strength of the medium. Thus, these findings are significant because they indicate that the corrugating process degrades the compressive potentials of the medium in the c.d. as well as in the m.d.

In addition to determining how forming affects compressive strength, tests are in progress involving bonding strength and the transverse shear characteristics of the medium. In Fig. 14 the Viscosity-Velocity Product (VVP) type bonding strengths in the machine direction of the hot and cold formed mediums are significantly lower than for the uncorrugated medium. Cold forming tends to give slightly greater reductions. It appears likely that the reductions in edgewise compressive strength are due to these losses in bonding strength. This seems particularly true in view of the delamination which accompanies compressive failure. Losses in shear

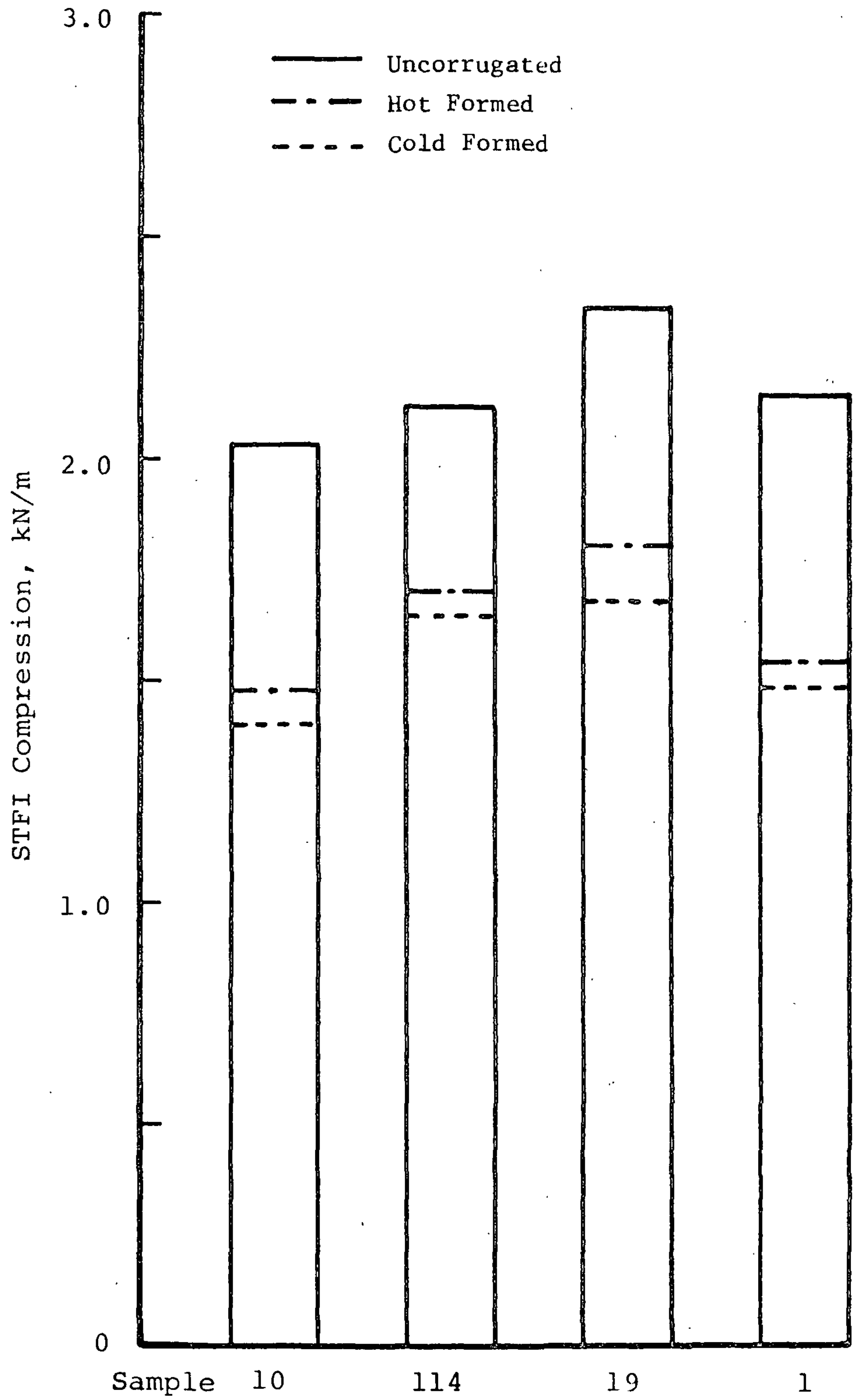

Figure 13. Effect of Forming on Cross-Direction Edgewise Compressive Strength

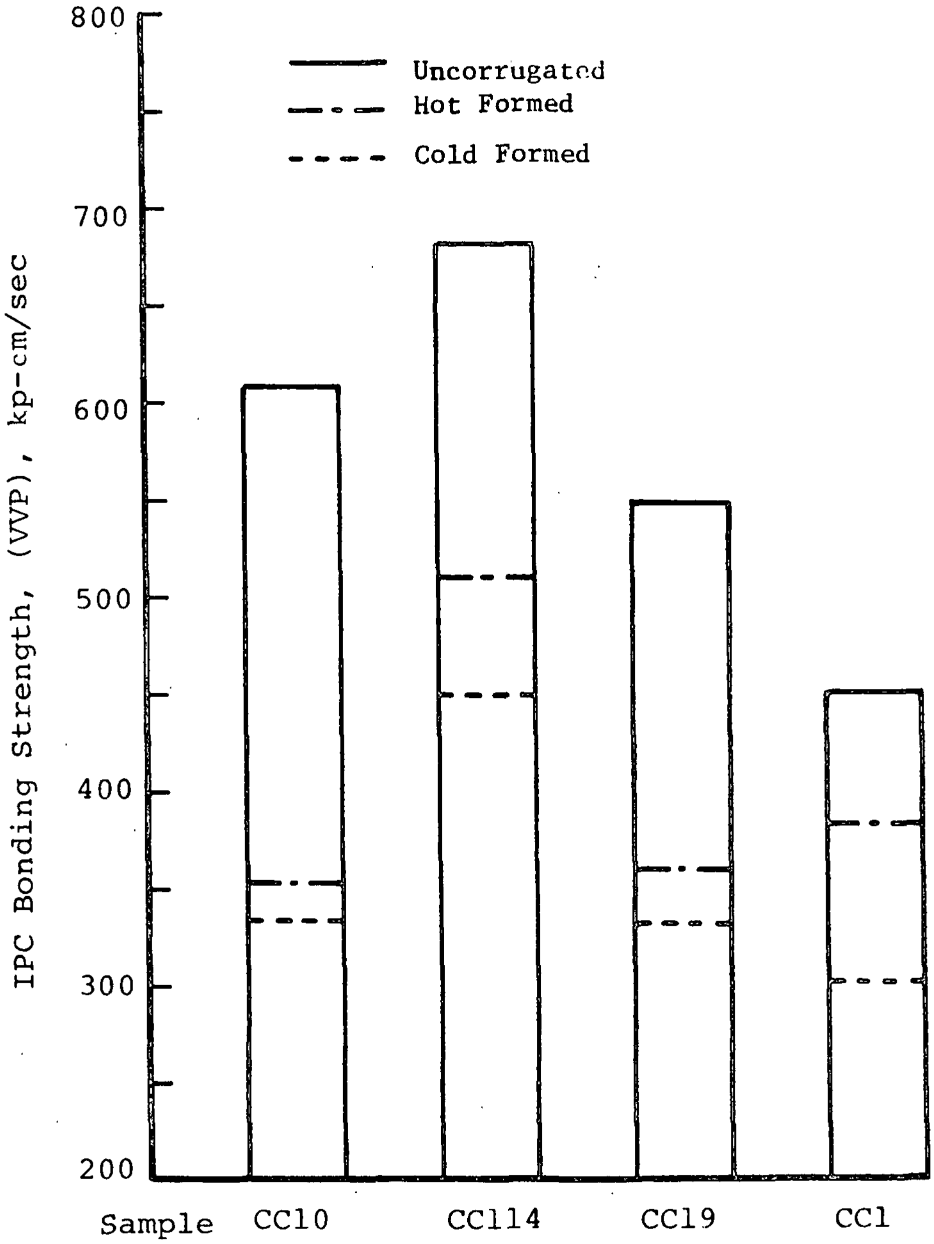

Figure 14. Effect of Forming on Transverse Bonding Strength in the Machine Direction

strength may also be involved and work is in progress to develop a transverse shear test. We should note that the bonding strength tests on the formed medium involve nonideal test conditions; therefore the results are probably only an approximation to the state of the medium after forming.

Thickness direction tensile (ZDT) bonding strength tests were also carried out as shown in Fig. 15. Generally the formed mediums exhibited lower ZDT strengths than the uncorrugated medium. However, the decreases in ZDT strength varied considerably from medium to medium and the decreases were probably not significant in some cases. These results appeared to be less revealing than the VVP type tests.

Briefly summarizing it appears that

1. The edgewise compressive and tensile strengths of medium are greatly reduced by fluting under both hot and cold conditions. We speculate that this is due to fiber-to-fiber bond damage during fluting.

2. Some mediums show more evidence of compressive strength reduction under cold conditions than under hot conditions. We believe this accounts for the lower flat crush obtained with such cold formed mediums.

3. We also noted that some mediums tend to exhibit more compressive degradation on the trailing flank than on the driven flank under cold fluting as compared to hot fluting conditions.

EFFECT OF TYPE OF FORMING STRESS

Work is in progress to determine how various types of stress such as exist in corrugating bring about compressive strength reductions. Our initial experiments involved prestressing medium in tension and combined bending and tension.

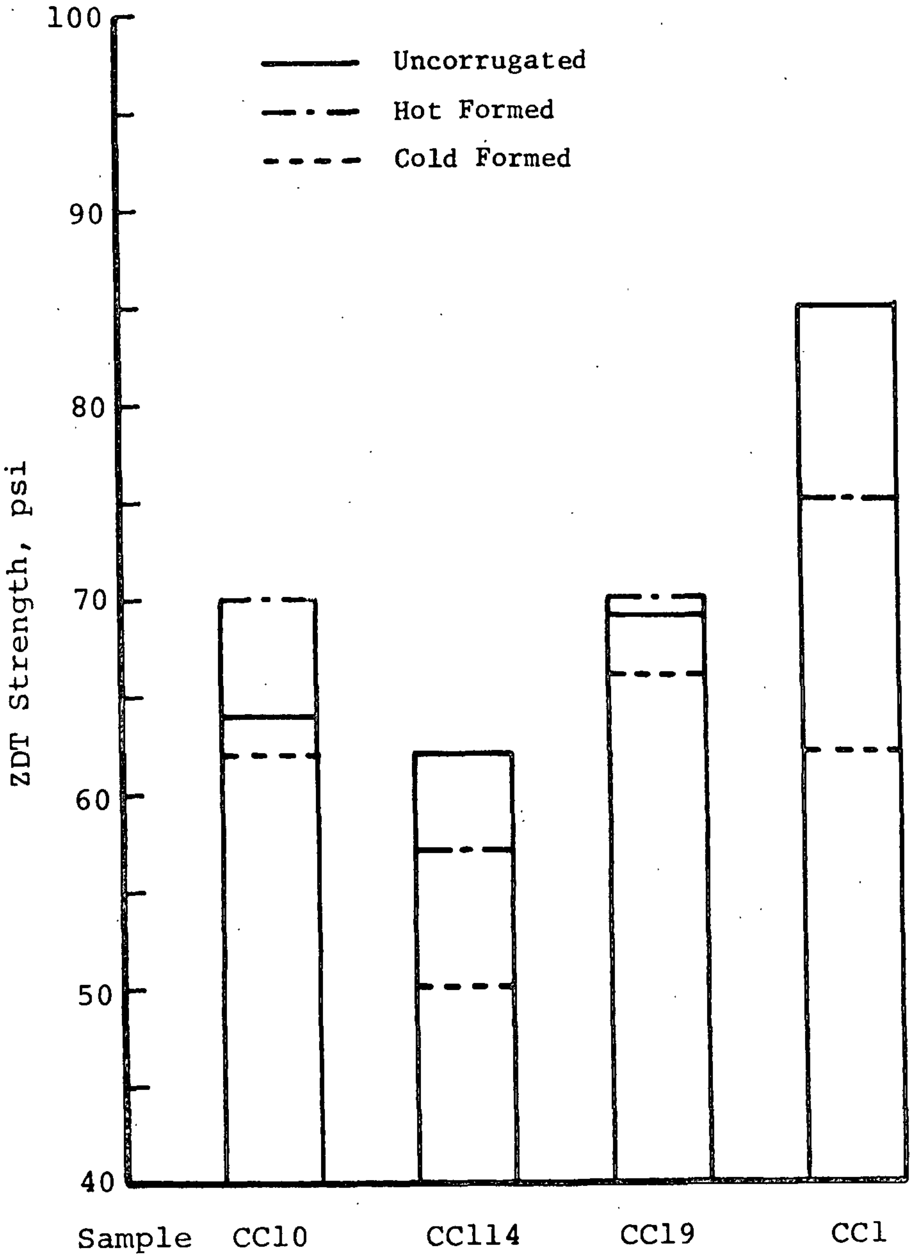

Figure 15. Effect of Forming Conditions on ZDT Strength

As a first step we loaded m.d. specimens of medium in tension to failure. The remnants were then evaluated for compressive strength using the STFI tester. Figure 16 shows that prestressing in tension only has little or no effect on compressive strength.

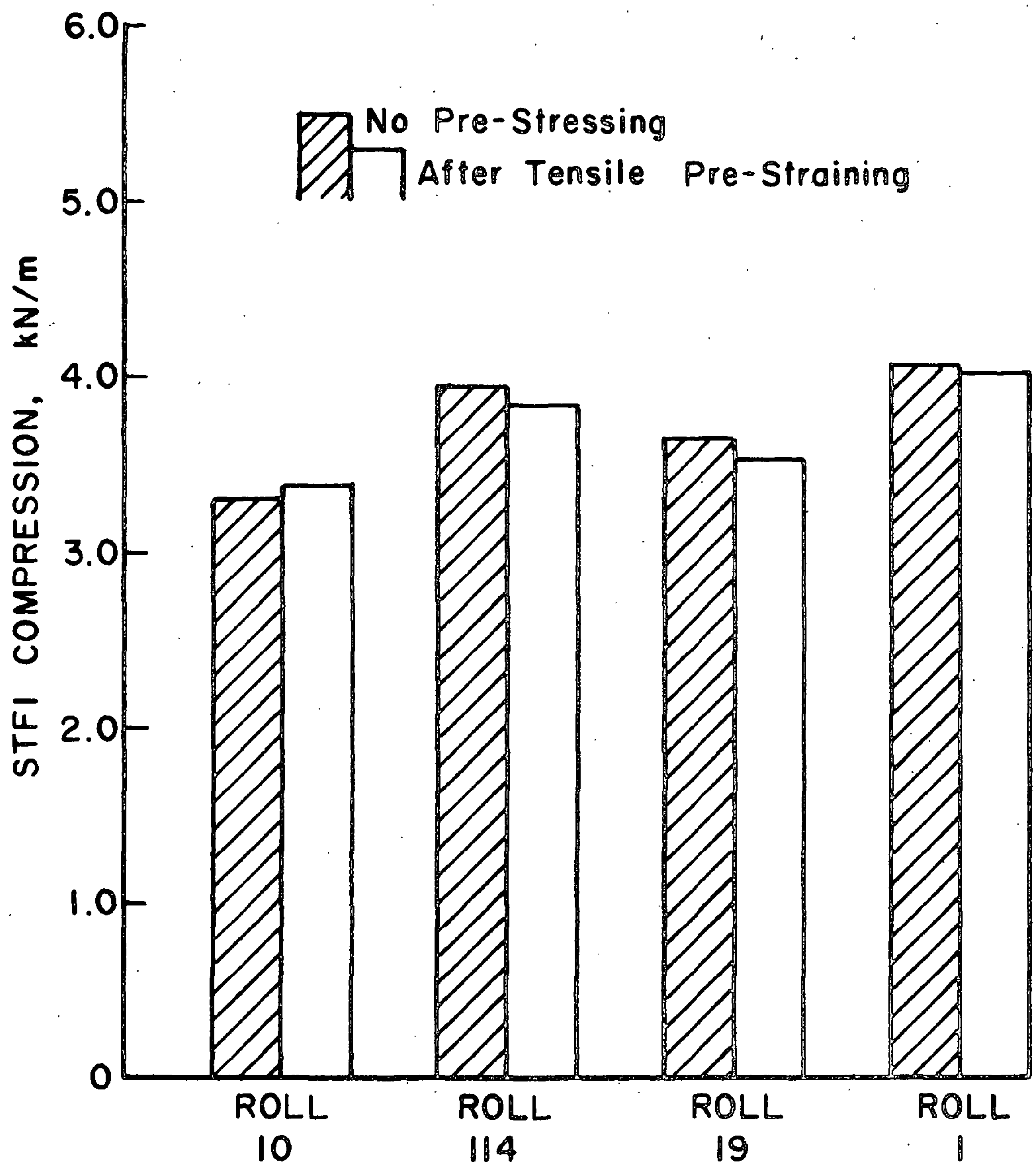

Figure 16. Effect of Tensile Prestressing on m.d. Edgewise Compressive Strength

In corrugating the onset of fracturing is usually gradual over a range of speeds. Also fractures do not usually propagate across the web "instantaneously" as occurs in long-span tensile tests. Within the labyrinth, it may be speculated that the medium is locally stretched far enough to produce fiber bond damage and to affect compressive strength but there is insufficient stored energy to cause tensile fractures to propagate. This behavior would be somewhat analogous to a short span tensile test on a "stiff" tester. In such tests there is often no visible indication of failure at the maximum load and no "instantaneous" failure is encountered. However, compressive strength might be lowered under such conditions.

When medium is preflexed by bending it around a small radius under low tension, the m.d. compressive strength after flexing is greatly reduced (Fig. 17). The smaller the radius, the greater the loss in compressive strength. Our results show that the bending stresses during forming could be partly responsible for the losses in m.d. compressive strength of the fluted medium. Because the tip and root radii of the corrugating rolls are relatively small, both bending and shear stresses are involved in forming medium to the flute contour as mentioned earlier.

The combined effects of bending and tension are illustrated in Fig. 18. Figure 18 shows that the compressive strength decreases rapidly as the wrap angle used in flexing increases from 0 to about 90°. Contact angles between the medium and the flute tip are about 90-120° near the center of the corrugating labyrinth (5,6). The results in Fig. 18 also indicate that the losses in compressive strength are aggravated by higher tensions and smaller radii. Past work has indicated that high web tensions occur in the corrugating labyrinth as friction between the medium and steel rolls increases. We believe that Fig. 18 indicates that higher web tensions will also affect properties of the formed board such as compressive strength, depending on the forming conditions such as temperature, speed, and moisture.

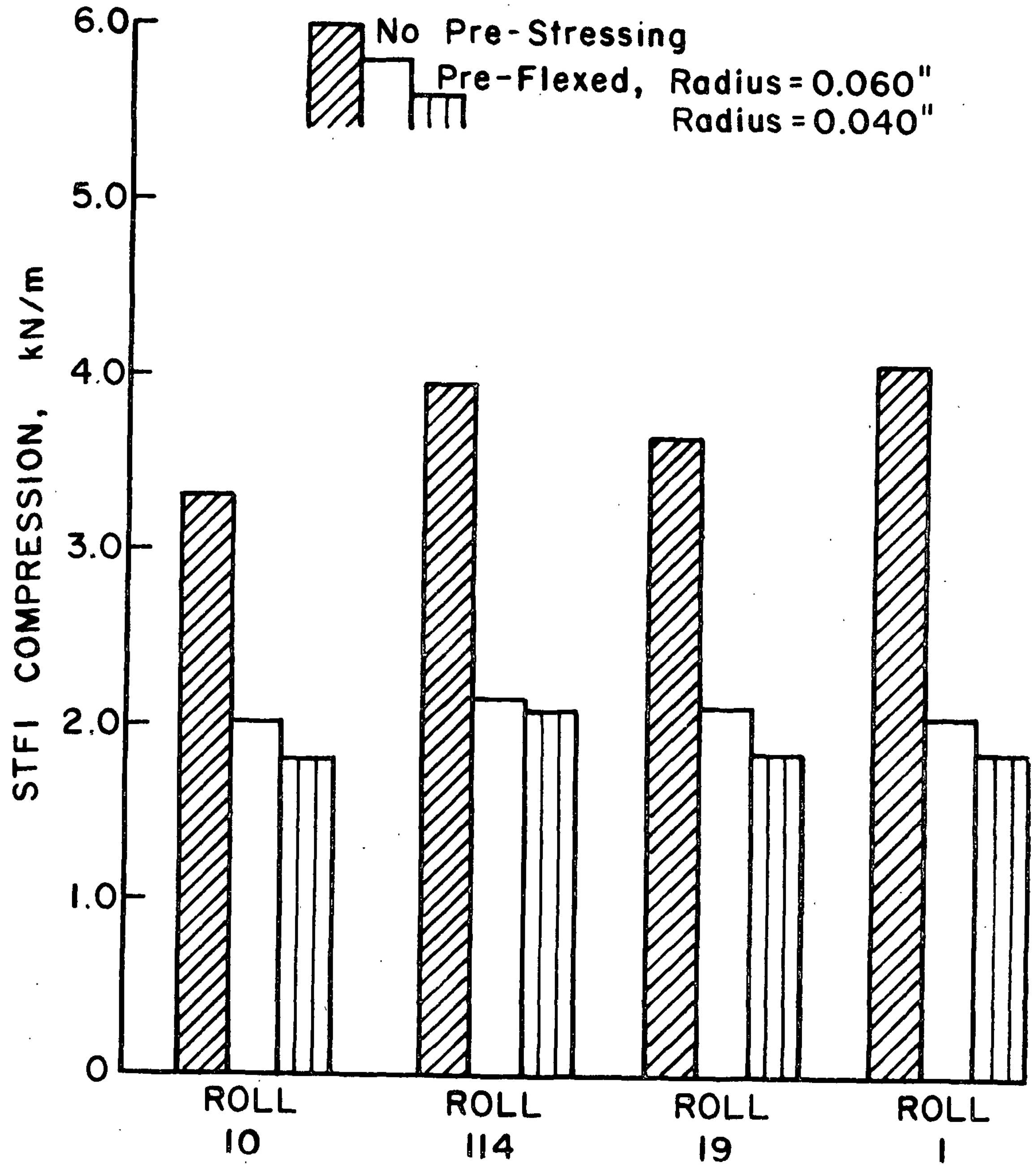

Figure 17. Effect of Bending Prestressing on m.d. Compressive Strength

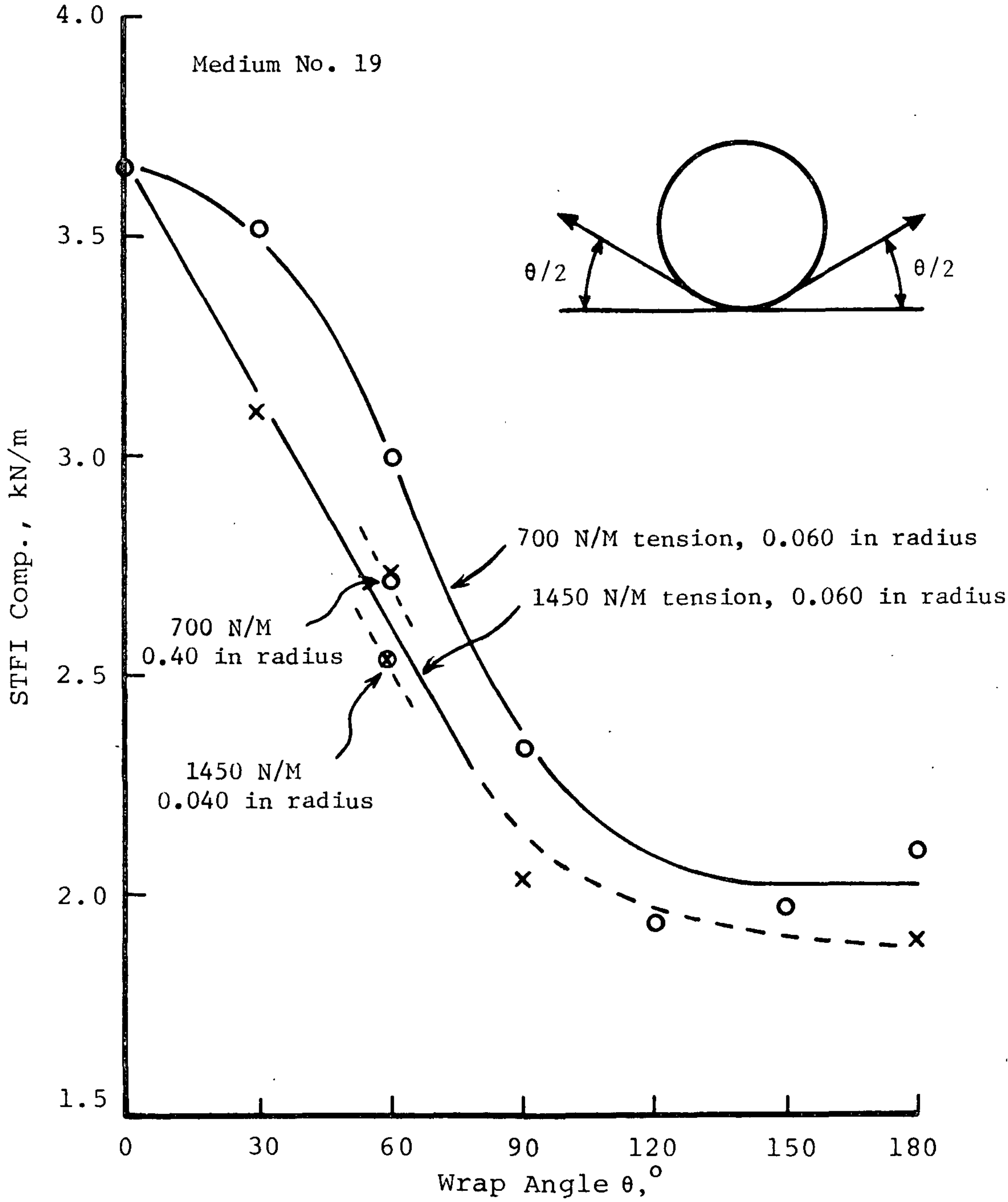

Figure 18. Effects of Tension and Flexing Conditions on m.d. Compressive Strength

The moisture content of the medium at time of forming will affect stiffness and moldability. Under cold forming conditions higher moisture contents should permit the medium to be bent to the flute radius with less damage and enhance its molding to the flute shape. This assumes that friction is held constant or reduced. We have partially confirmed this in past cold corrugating trials over a limited moisture range which indicate that higher moisture contents promote higher flat crush.

To determine how flexing at various moisture contents would affect compressive strength, trials were carried out at RH levels ranging from about 15% to 90%. Figure 19 shows that the compressive strengths of the flexed mediums decreased at about the same rate as the unstressed control at high levels of moisture.

Limited trials were also carried out in which the medium was preflexed at various moisture contents and then reconditioned to 50% RH prior to compression testing. It was speculated that the flexing at high RH would have less severe effects than at 50% RH and, hence, would not reduce compressive strength as much. However, the effects of the high RH flexing seemed to result in about the same compressive strengths at 50% RH as flexing and testing at 50% RH. We did note, however, that the reductions in compressive strength for the various mediums seemed to be related to the VVP bonding strength.

FORMING: SHEAR AND CLEARANCE FACTORS

In the forming process large bending and shear stresses are induced in the medium as it is formed to the flute contour. A qualitative analysis shows that formation of the flute cannot occur by pure bending because this would require very large machine direction stretch values (1,5,6).

The results of a qualitative analysis are illustrated in Fig. 20. If the medium accommodates itself to the flute contour by bending only (no shear strain)

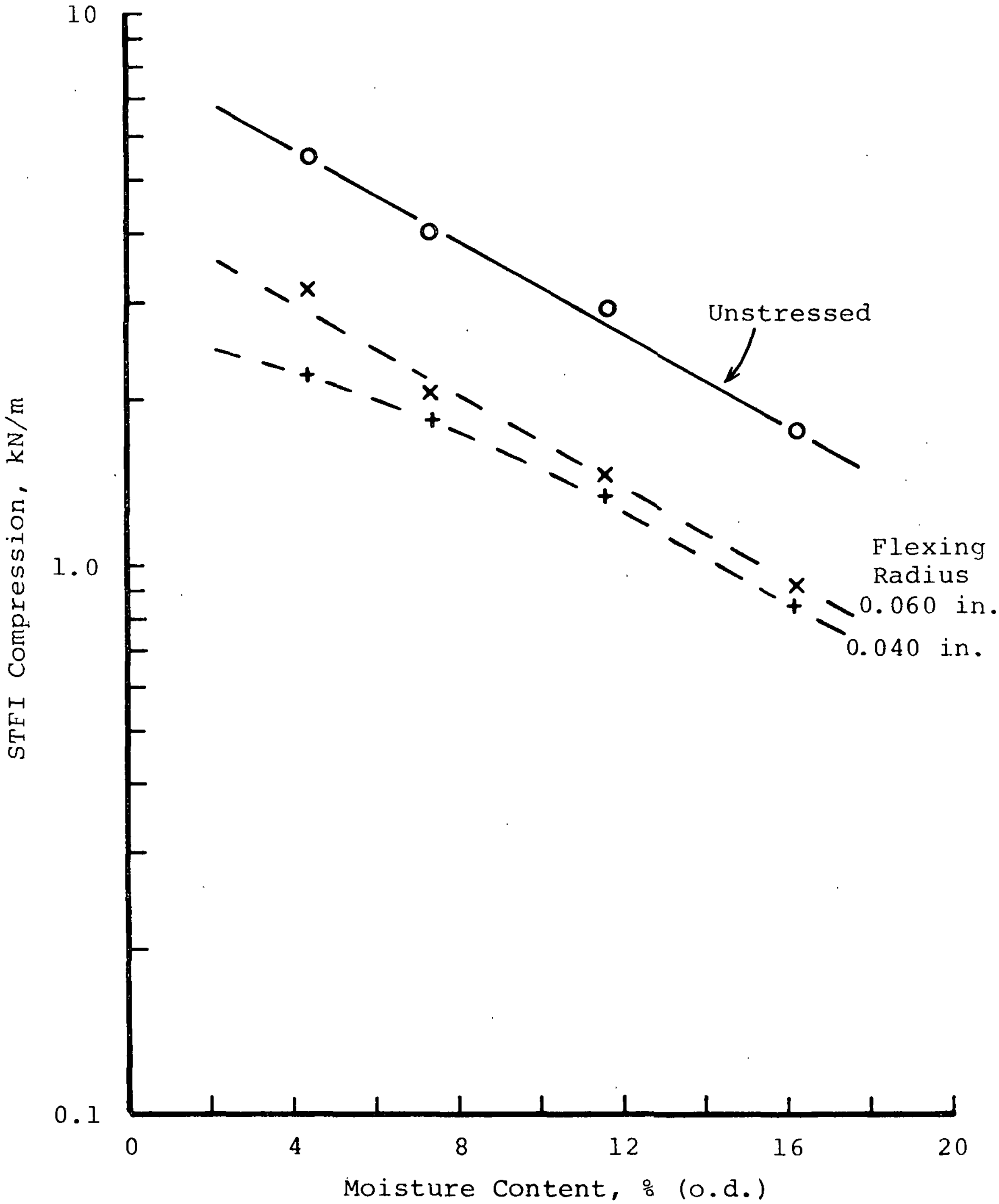

Figure 19. Effects of Flexing at Various Moisture Levels on Compressive Strength

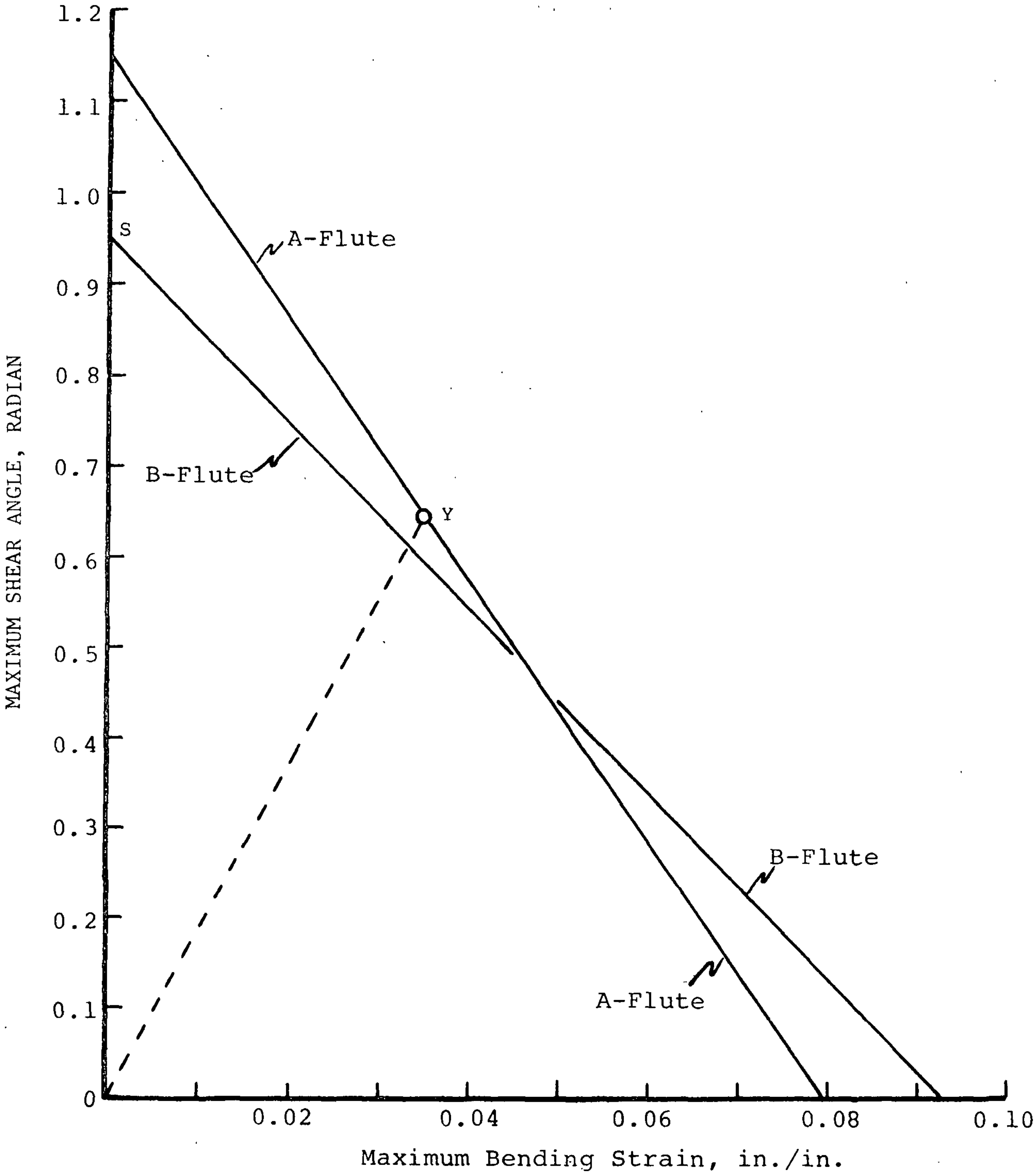

Figure 20. Relationship Between Bending and Shear Strain Required for Flute Forming [Ref. (5)]

the required machine direction strain is at least 8%. Thomas (6) indicates even higher stretch values may be necessary. On the other hand, if only shear stresses were involved, a very high shear angle would be required and the medium would essentially behave like a deck of cards. The apportionment of the strain between bending and shear will depend on the ratio of the bending and shear stiffnesses (elastic and unelastic) of the medium. If the medium is stiffer in bending than in shear, flute formation will involve large shear strain and small bending strain, and vice versa. As an example for given shear and bending properties the strains will increase along some path OY in Fig. 20 as the flute is formed. The intersection point Y shows what strain levels the medium must withstand. In this example, the medium would have to have an available stretch in excess of 3.5% and an allowable shear angle in excess of 0.65 radian to form without failure. Thus we believe that shear properties of the medium are important in corrugating as in folding operations.

Preliminary ultrasonic measurements of transverse shear and extensional moduli are shown in Table II. The m.d. tensile modulus E_x is 30-40 times greater than the transverse shear modulus G_{xz}. The low shear moduli indicate that a portion of the molding will depend on shear.

TABLE II

ULTRASONIC SHEAR AND IN-PLANE MODULI

	Medium Sample Number			
	10	114	19	1
MD in-plane modulus, (E_x), psi	588,000	804,000	645,000	929,000
Shear modulus G_{xz}, psi	19,300	19,000	18,400	24,200
Ratio: E_x/G_{xz}	30.4	42.2	35.0	38.5

Transverse shear measurements are difficult to carry out. Only a few techniques are mentioned in the literature. We are attempting to develop a technique for obtaining shear load-deformation curves. These will supplement and extend the ultrasonic measurements which are restricted to "elastic" displacements. Initial results indicate that the mechanical measurements of the transverse shear moduli will be lower than the ultrasonic values as expected due to strain rate effects. However, considerable work is required to improve the technique so as to better characterize material performance in forming and structural performance applications.

An analysis of clearance in the labyrinth shows that a potential pinch point exists about 1/2 flute ahead of the center line (see Fig. 21). In past work at the Institute, high speed motion photography shows that fracturing occurs before the medium reaches the centerline, also by about 1/2 flute. The lower roll begins to drive the upper roll at a location about 1/2 flute ahead of the center line. If the full amount of medium has not been drawn into the last half flute, relatively high tensile strains would be imposed due to the pinching action. This would result in the risk of greater medium damage and the occurrence of fracture.

FLUTE GEOMETRY vs. FORMING CONDITIONS

In general, the differences in flat crush between cold and hot formed board would be expected to depend on medium characteristics and/or flute geometry. Our current research has been directed to determining whether geometry or material differences due to forming conditions are more important in affecting board quality. The preceding work showed that some cold formed mediums exhibited lower compressive strength after fluting than hot formed board. In these cases the cold board also gave lower flat crush than hot board. In order to determine if flute profile

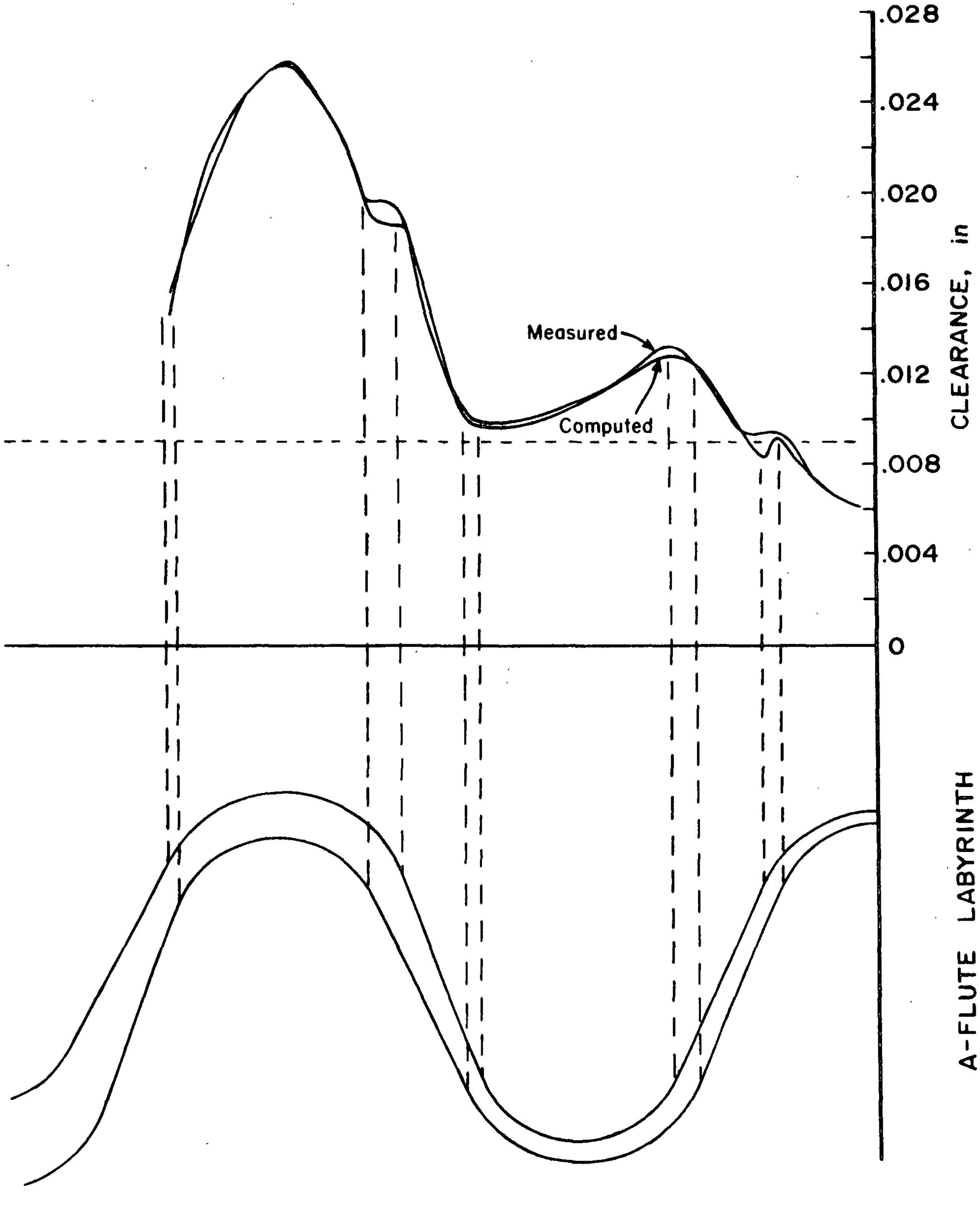

Figure 21. Clearance in Labyrinth

(geometry) differences are also obtained under hot and cold corrugating conditions, a detailed analysis of flute profiles has been carried out.

For this purpose an Autech model AKR Laser Dimension gage was employed to measure the flute profiles (29). The profiles were measured by passing a web of single-faced board under the laser at a controlled speed. The signal from the laser sensor is recorded and then analyzed.

Three single faced boards fabricated using mediums 1, 19, and 114 were analyzed for geometry differences caused by the hot and cold corrugating process. The single faced boards were fabricated at a speed of 200 FPM under normal but controlled conditions of web tension and corrugating pressure. The average flute profiles of the cold and hot formed single faced board in Fig. 22 show that cold and hot formed flutes are similar in shape. However both cold and hot formed flutes are unsymmetrical and to about the same degree. The unbonded tip is somewhat flattened and rounds-off more gradually to the trailing side than to the drive side. We believe these symmetry differences are related to the different forming conditions for the driven and trailing sides. In addition the dynamic forces imposed in the forming of the bonded and unbonded tips are somewhat different as noted in Fig. 5. While the dynamic forces vary in magnitude with corrugator operation it appears that less molding force is applied to the unbonded tip as a result of the drive action.

We also observed in the flat crush test that the unbonded tip collapses first and more rounding-off occurred on the trailing side. This may be due to the above geometry differences.

Figure 22 shows that the cold formed flutes have slightly higher caliper as noted in past studies. There were slight indications that, in two cases, cold formed

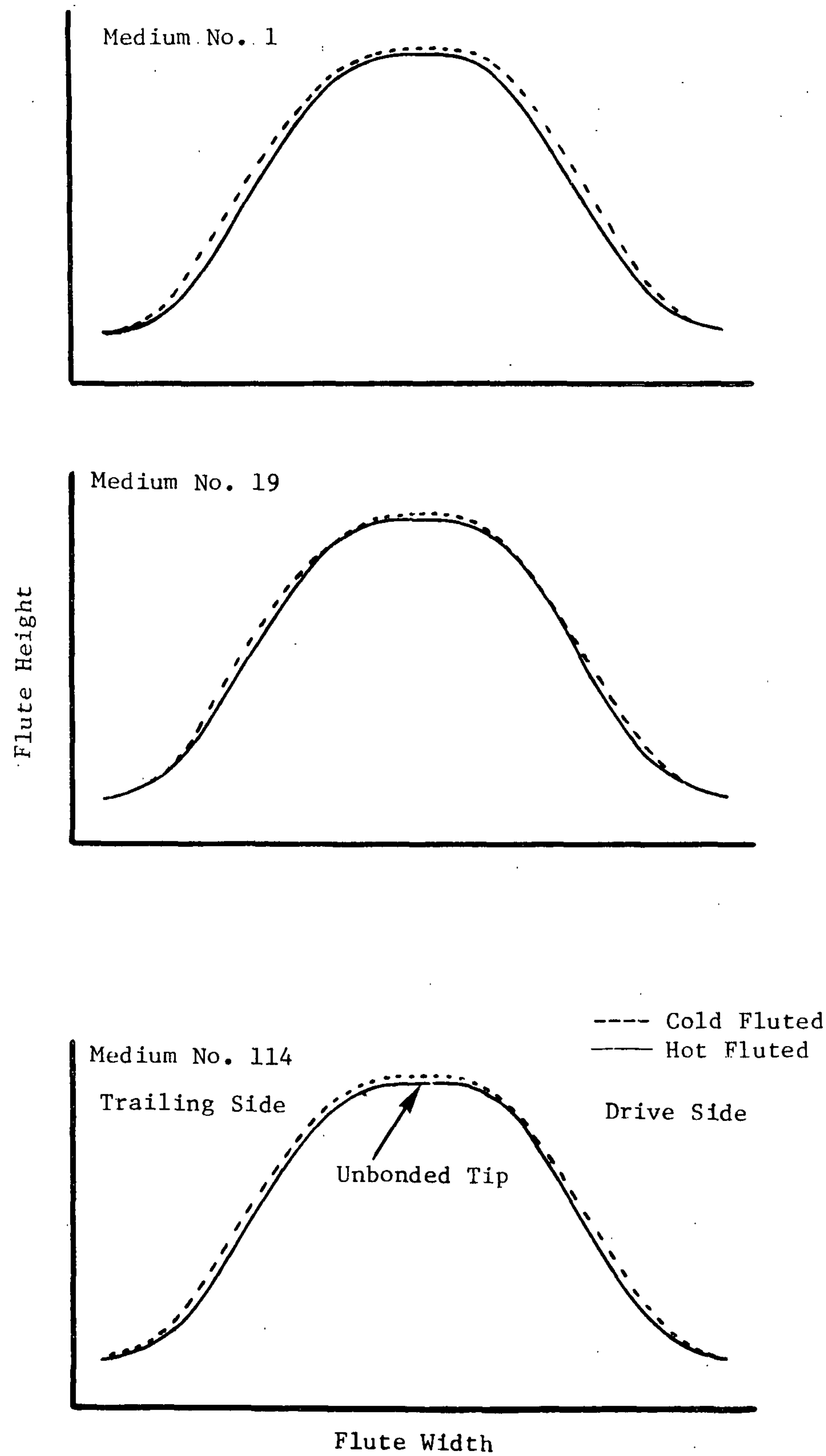

Figure 22. Flute Profile Shapes

flutes were more symmetrical in shape; in one case, the hot formed flute was more symmetrical.

The effects of flute geometry on board performance (flat crush, flexural stiffness, short column compression, top-to-bottom compression, etc.) has not been theoretically evaluated as yet. Of particular interest is the flat crush performance. As the hot and cold formed flutes are very similar in geometry, we expect that the differences in flat crush performance between some hot and cold formed mediums are due primarily to differences in the material properties rather than shape.

MECHANICS OF FLAT CRUSH

One of the specific purposes of our forming research has been to determine why some mediums yield ultimate flat crush strengths which are different for hot and cold forming. In the "Background" discussion we noted that forming conditions appeared to have no major effect up to the first peak of the flat crush load-deformation curve (see Fig. 6, for example). Thus hot and cold formed board should respond similarly to normal converting stresses of the flat crush type.

However, some cold formed mediums exhibit lower ultimate flat crush strengths than under hot conditions as shown in Fig. 6. In both cases the mediums deform into a hat-shaped frame (Fig. 11). However, the cold formed medium seems to deform less symmetrically as shown in Fig. 10 and 11. In most cases, the second peak in the load-deformation curve (Fig. 6) is absent or only manifests itself as an inflection in the curve if the cold flat crush is low. We found earlier that such cold formed mediums exhibited lower edgewise compressive strength in the flank/tip regions. It appears that the compressive losses affect the formation of the "plastic" hinge points during crushing and the ultimate load.

Flat crush loads are resisted by the flanks of the flute. Figure 23 shows that flat crush loads (expressed as load per unit length of flute side wall) are substantially lower than the STFI compressive strengths of the uncorrugated medium. They are also lower than the compressive strengths exhibited by the formed mediums in the flank/tip regions. While the flank/tip compressive strengths correlate with the flat crush results (Fig. 9), the differences in magnitude in Fig. 23 indicate that the mechanism controlling flat crush load-deformation behavior needs to be placed on a sound theoretical basis.

We pursued two approaches concerned with developing a better understanding of the flat crush load-deformation curve. The more fundamental approach was directed to developing a finite element model for the flat crush load-deformation curve. The second approach utilized a simple frame analysis as a conceptual way of explaining various aspects of ultimate flat crush behavior.

Finite Element Analysis

The initial finite element solution allowed for the large deflection behavior of the shell structure. However, as a first step the medium properties were considered to be linear-elastic. This model appeared to provide reasonable estimates of the initial slope of the flat crush curve, particularly when transverse shear effects were considered. The model could not adequately describe flat crush loads beyond the first peak load. Among other things, the results indicated that it would be necessary to account for material nonlinearities as well as large deflection. However, this resulted in a more complex model. To reduce the modeling costs and time, only five elements over a 1/4 flute length were employed. This results in a crude representation of the flute shape (Fig. 24).

Several different kinds of finite elements were needed in the nonlinear structural models. They were an elastic-perfectly plastic hinge, elastic hinge,

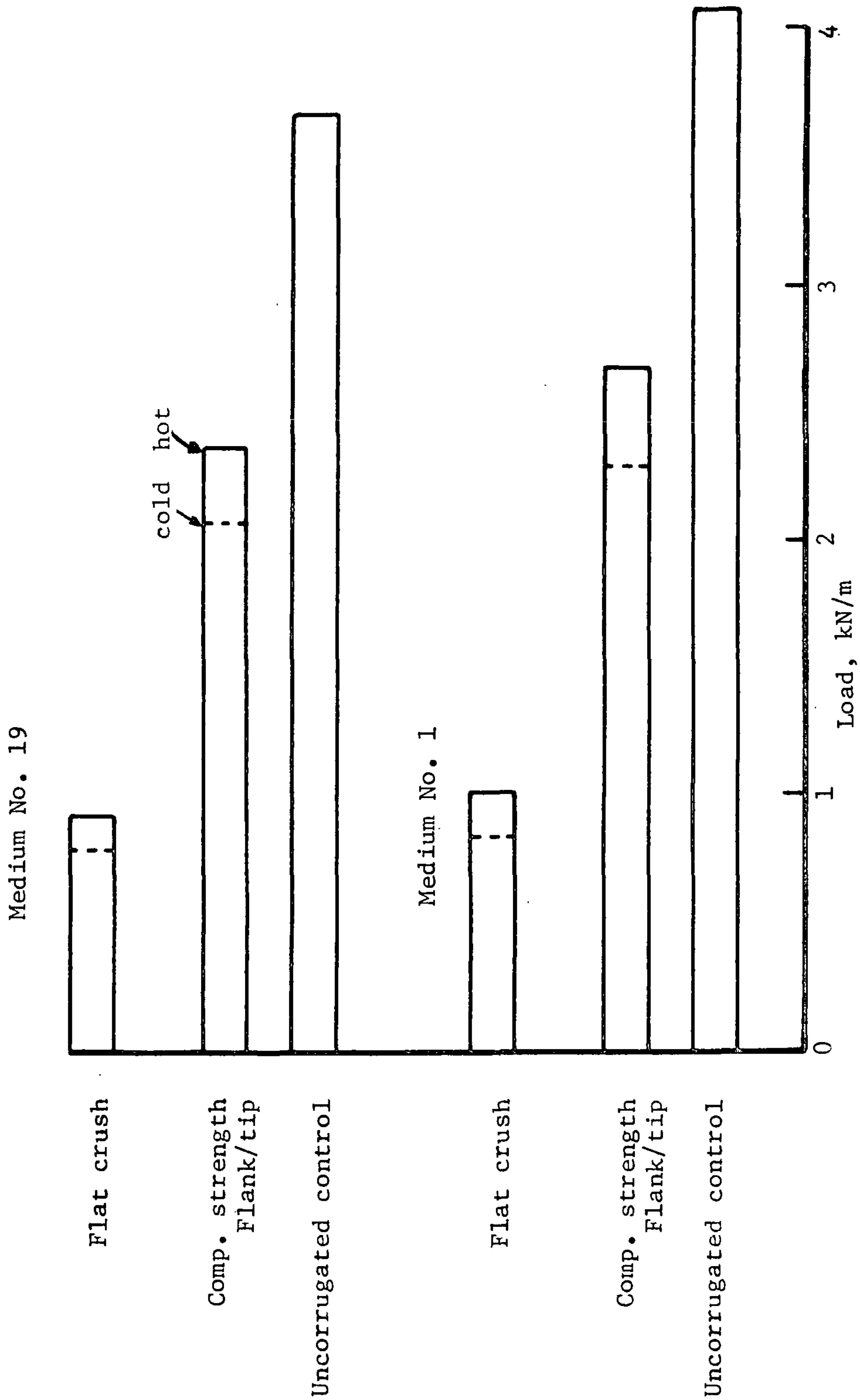

Figure 23. Flat Crush and m.d. Edgewise Compressive Strength Comparisons

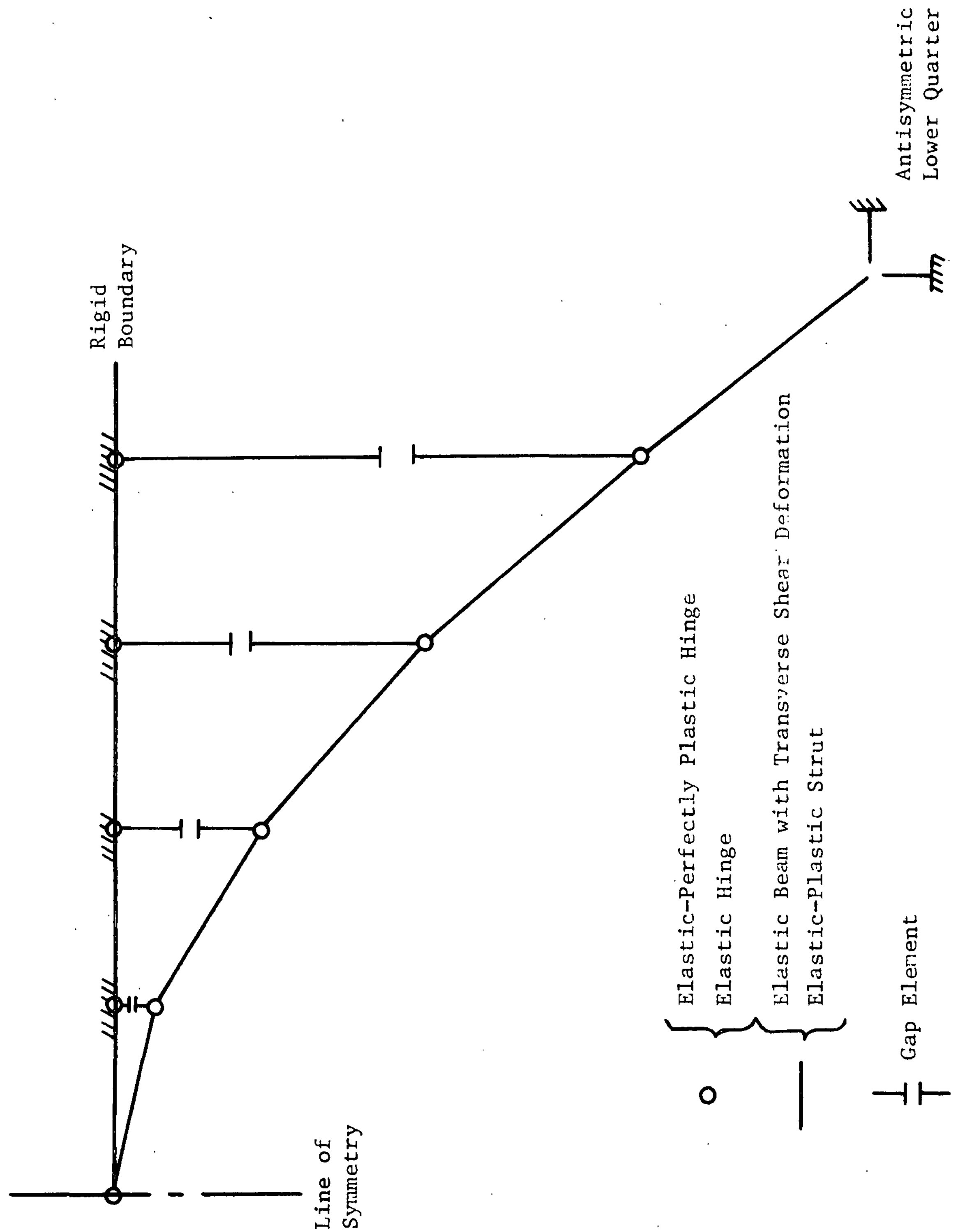

Figure 24. Quarter Symmetric/Antisymmetric Flute Model

elastic beam, elastic-plastic strut, and gap element, as shown in Fig. 24. We had to utilize several different kinds of finite elements because there was no single finite element available in the element library which incorporated all of the necessary material characteristics that were needed to model paperboard. The elastic-perfectly plastic hinge and the elastic hinge were used to model the bending characteristics of the medium at large rotations. The elastic beam elements were needed to incorporate transverse shear deformation characteristics into the model. The elastic-plastic strut was used to model the in-plane compressive stiffness of the medium. Finally, the gap elements were used to model the effect of the rigid boundary of the liners on the medium shell structure. The characteristics of the elastic-plastic hinge, elastic hinge, elastic beam, and strut were chosen so that compositely they would model the overall material behavior of the medium in a general state of compression. Ideally, it would have been desirable to use a beam element which included all of the necessary material characteristics, i.e.,

1. Transverse shear.
2. Tension/compression.
3. Nonlinear material behavior.

Nonlinear material properties for compression and tension were experimentally obtained (Fig. 25). The compressive properties were used to describe the material response of the strut finite elements. Both the tensile and the compressive stress-strain curves (Fig. 25) were needed to compute the elastic-plastic hinge response (Fig. 26). The solid line is the computed nonlinear hinge response. Since the hinge element could only exhibit elastic-perfectly plastic behavior, the response indicated by the dashed line was used in the structural model. The elastic hinge (Fig. 26) was assumed to have a stiffness of 1 inch-lb/RAD. This value needs to be experimentally confirmed for the large rotational regime.

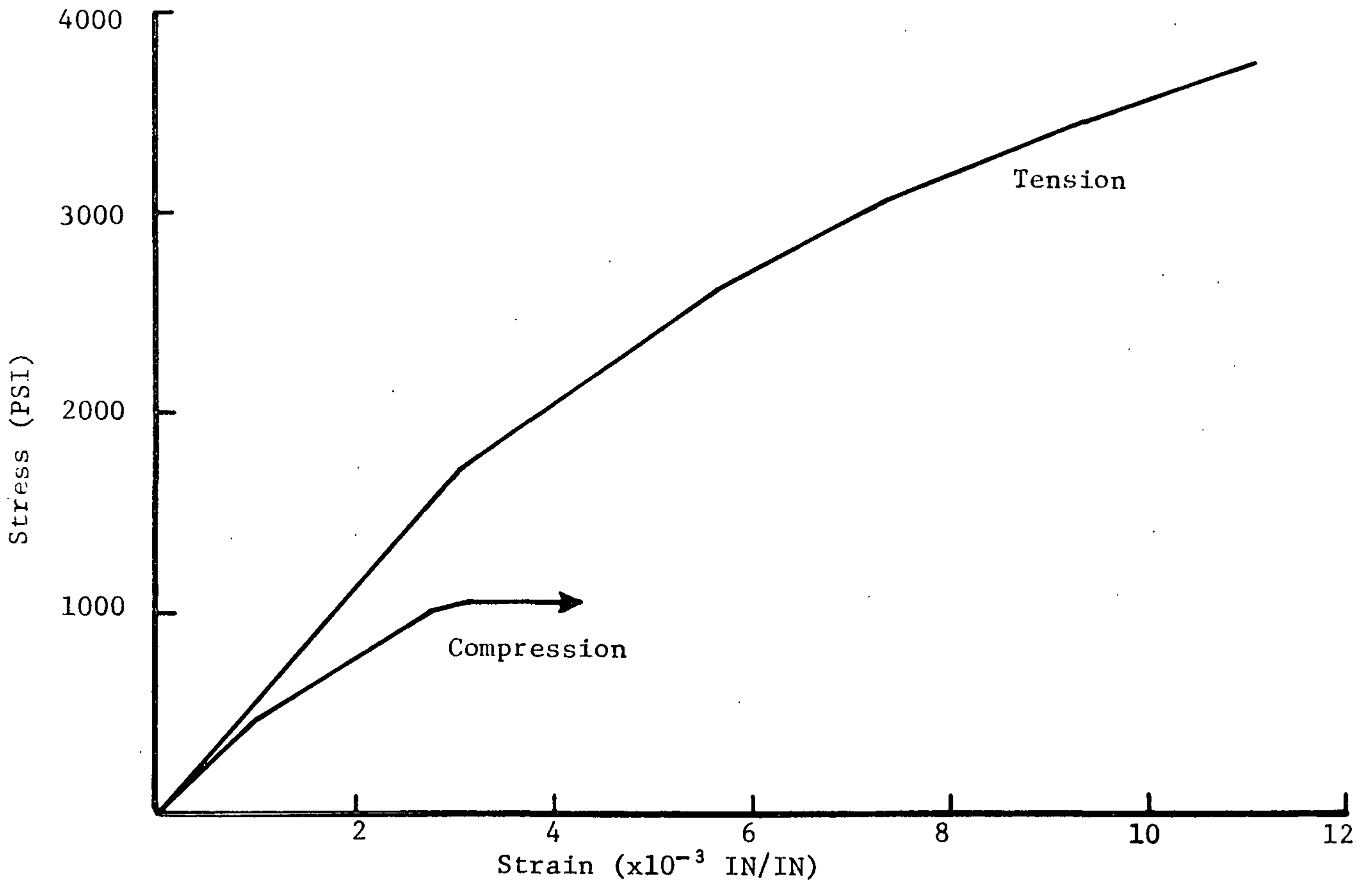

Figure 25. Tensile and Compressive Stress-Strain Curves for the Uncorrugated Medium

The predicted large deflection response to flat crush loads of the board after including nonlinearities is compared to the experimental results in Fig. 27. We expected that including the material nonlinearities would significantly lower the load-deflection curve relative to the elastic case. This was confirmed as can be seen by comparing the two dashed curves.

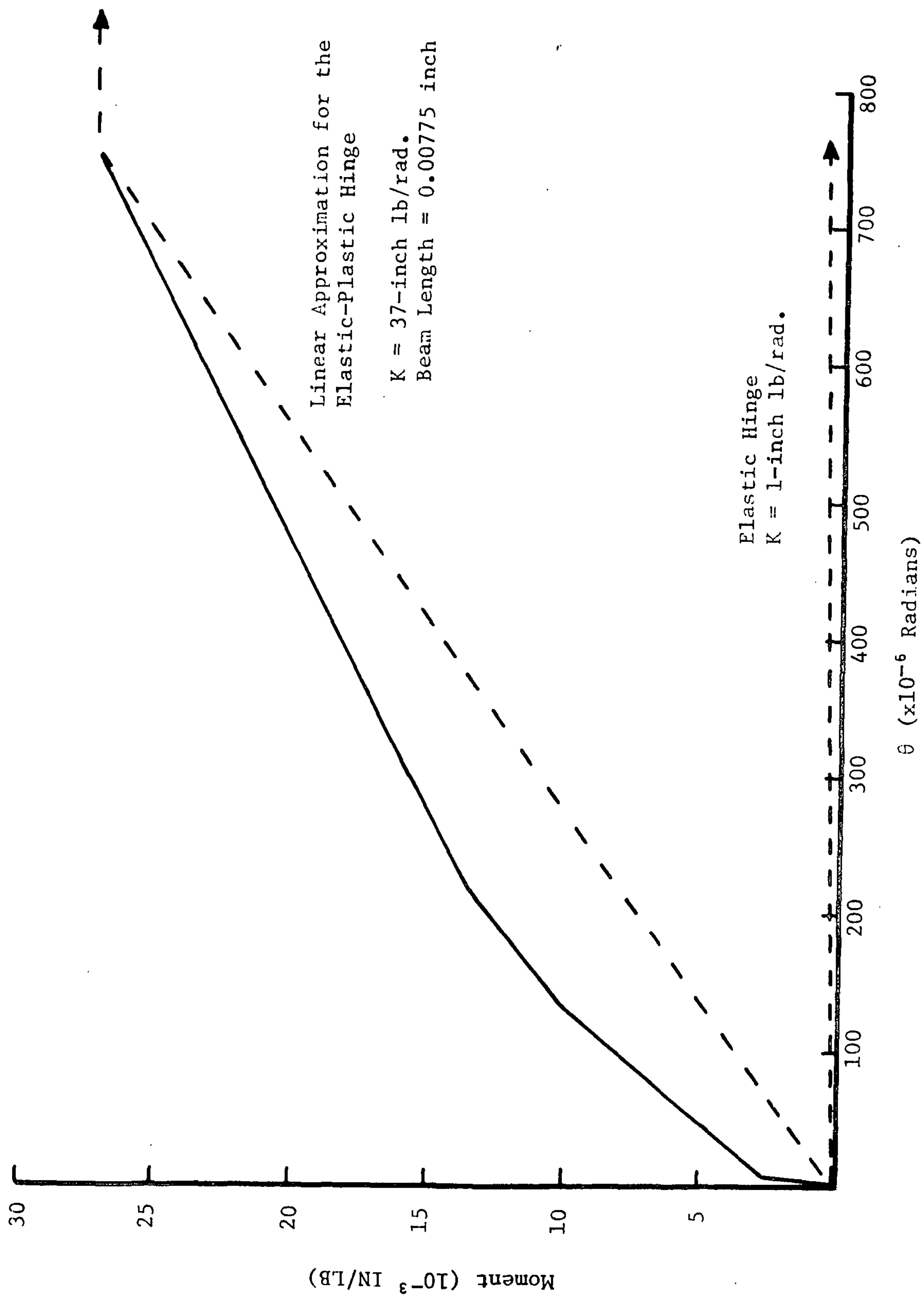

Figure 26. Load-Deflection Response for the Hinges

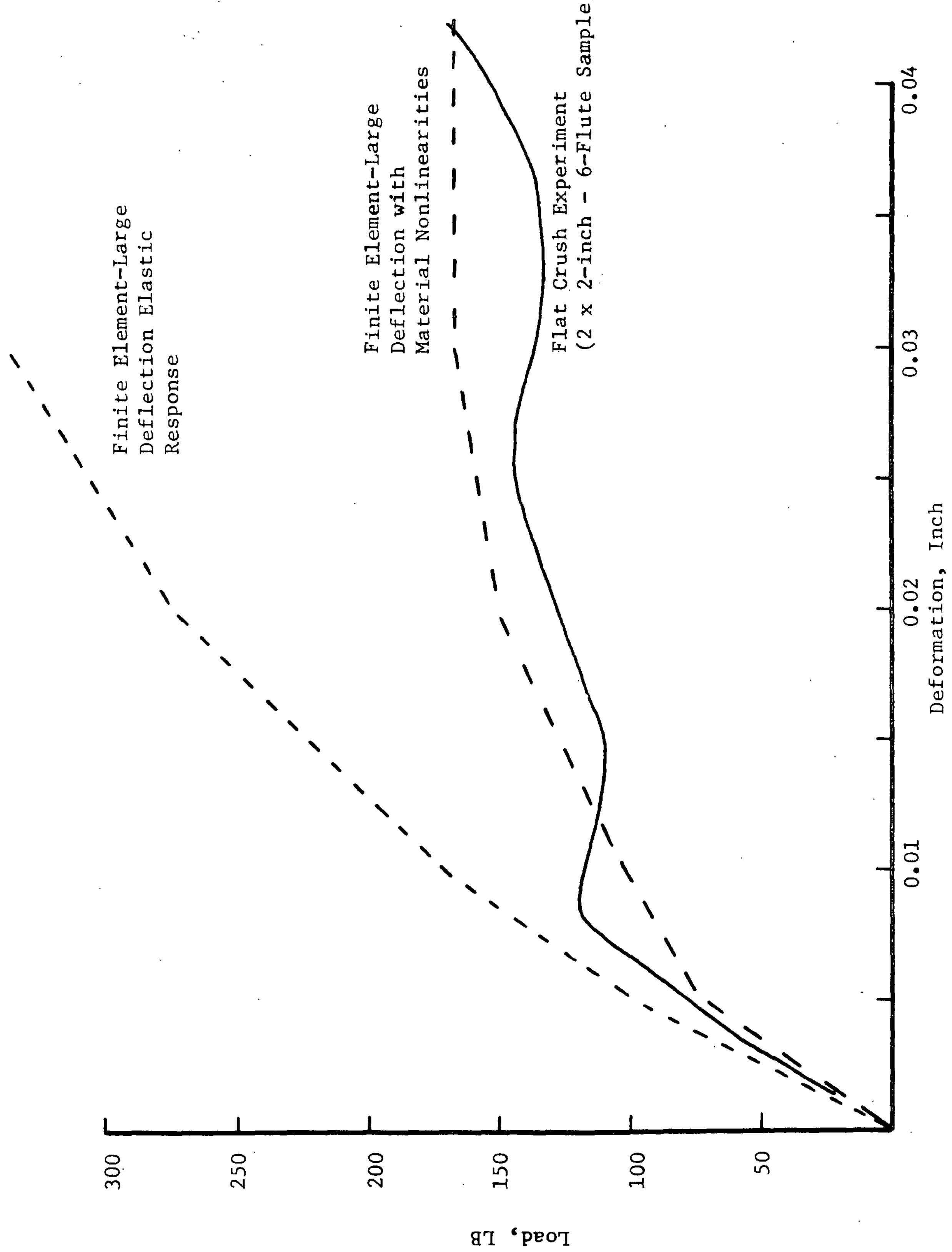

Figure 27. Elastic and Nonlinear Model Load-deflection Responses for Flat Crush

The flat crush response is plotted to a larger scale in Fig. 28. The general shape of the experimental response curve was captured but the local instabilities (i.e., dips) were not. Possible explanations for this include:

1. Difficulties in evaluating all the material properties needed - e.g., the transverse shear load-deformation curve. Also no allowance was made for changes in properties due to forming.

2. Incomplete material description for large rotational behavior.

3. Incomplete understanding of material nonlinearities related to coupling effects between axial stress, bending stress, and transverse shear.

4. Too few finite elements were used: for this first try, the shell structure was divided up into only five segments.

5. Stress stiffening as well as large deflection may be needed.

6. The large deflection approach used in this particular computer code is too approximate: another code may be needed.

7. Flute geometry was specified to be a perfect sine wave. A nonsymmetric nonideal flute profile may be needed as described in the flute geometry section.

Another aspect observed in the experiment that was not captured by the finite element model is the almost complete vertical straightening of the flute sides during flat crush. The predicted flute profiles show no pronounced tendency toward this vertical straightening (Fig. 29). However, the simpler linear-elastic, large deflection model captured the vertical straightening (Fig. 30). Note that the deflected shape approximates the observed hat shape of the medium near failure.

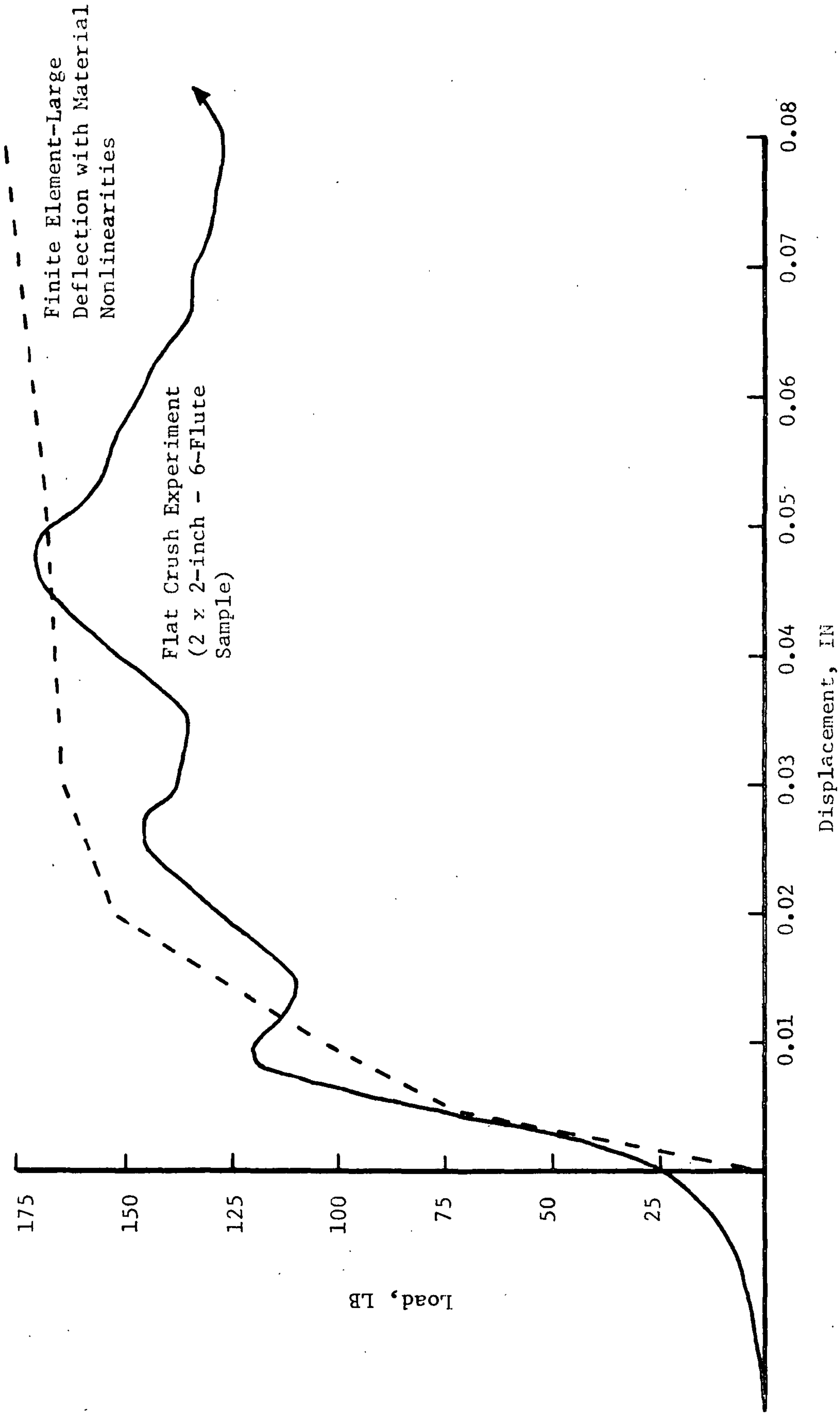

Figure 28. Predicted and Measured Load-deflection Responses for Flat Crush

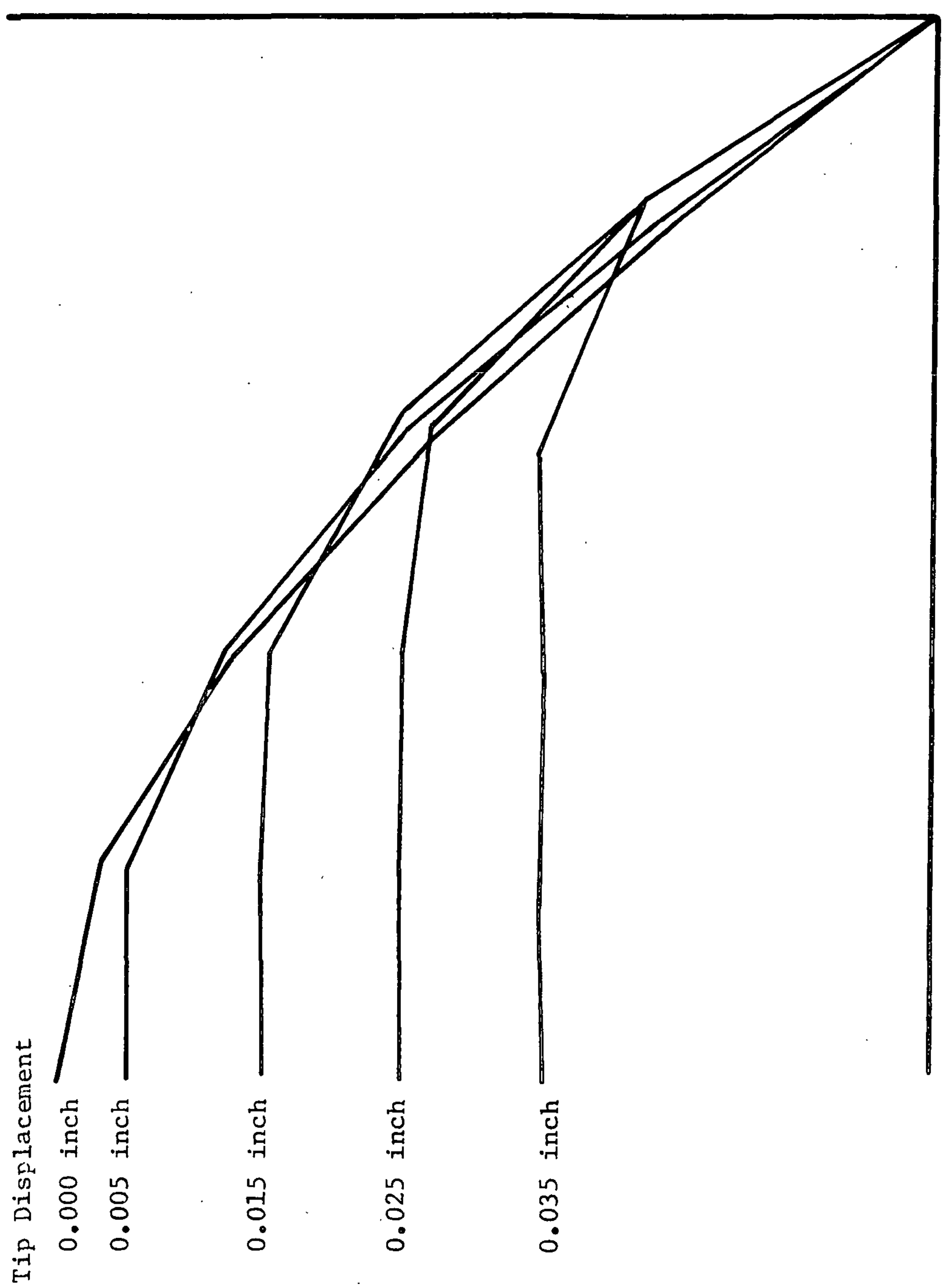

Figure 29. Deflected Flute Profiles for Quarter Flute Model Allowing Large Deflections and Material Nonlinearities in Analysis

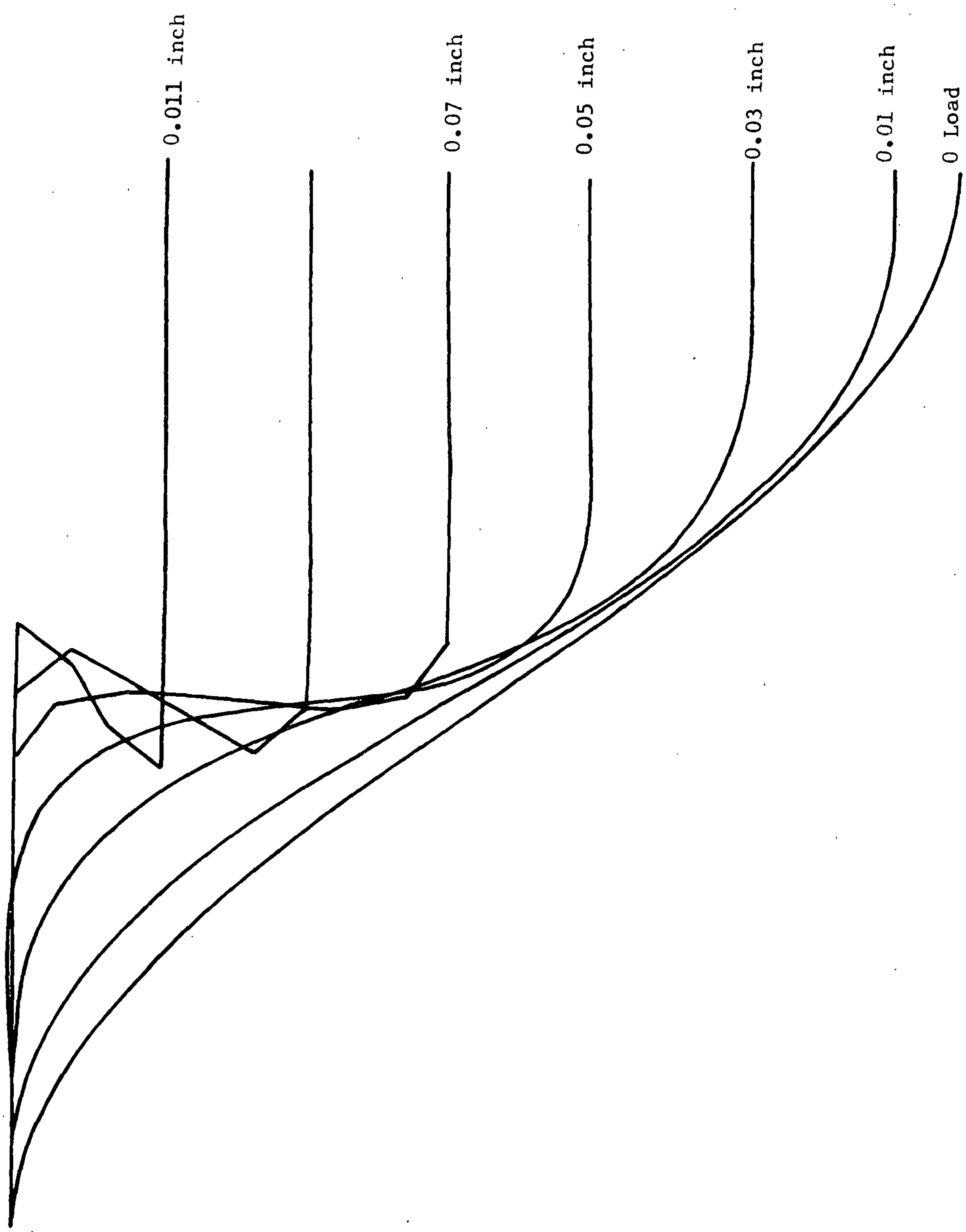

Figure 30. Deflected Flute Profiles for Half-Flute (Large Deflection, Linear Elastic Model)

Currently, we do not know if this difference in behavior is a result of the simplified finite element model (only 5 elements per 1/4 flute), or the material property assumptions.

We believe that Fig. 28 and 30 illustrate the potential ability of finite element models to predict the entire flat crush load-deformation curve. Such models would allow us to better define the characteristics of the medium which govern not only flat crush failure but also the initial load behavior so important in converting. However, the full potentials of finite element analysis cannot be realized until better methods are developed to evaluate the physical properties of medium and board. For this reason futher work on this model has been stopped pending the development of better material models in fundamental studies at the Institute.

Frame Analysis

In the final stages of the flat crush test the medium forms a frame-shaped structure (Fig. 31). Timoshenko (32) discusses a frame buckling case which is somewhat similar to flat crush. This results in an Euler type column equation where the end-condition coefficient depends on the thickness of the medium and the frame dimensions. Thus

$$P = k^2 \; E \; I/\ell^2 = k^2 \; Et \; (t/\ell)^2 \tag{1}$$

where P = maximum load,

E = modulus of elasticity in direction of load,

I = moment of inertia, = $wt^3/12$

w = column width,

t = thickness,

ℓ = frame height,

and k^2 = frame coefficient dependent on the lengths of the elements and moments of inertia (I, and I_1, in Fig. 31).

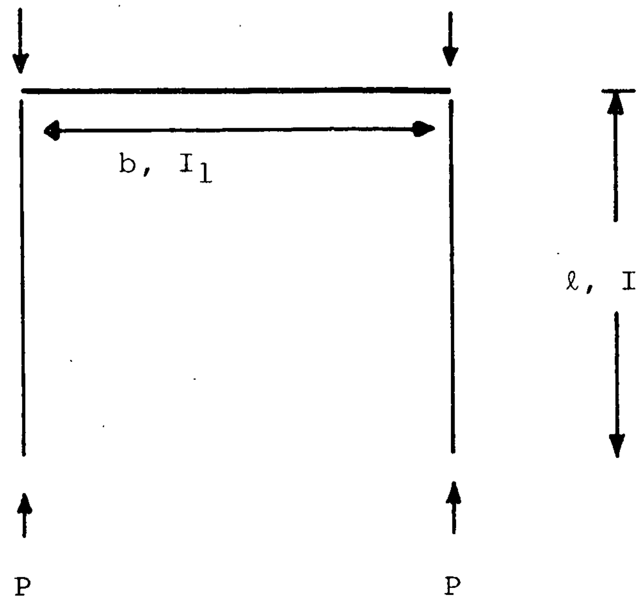

Figure 31. Frame Buckling - Lateral Displacements Permitted

The frame equation provides a conceptual way to explain such effects as flute geometry, the weight or thickness of the medium and various papermaking factors. Brecht and Bachmayer (30) in an extensive investigation showed that "generally everything which increases the elastic modulus" increases Concora strength. They also noted that Concora strength was quite sensitive to thickness. They cited the following: (1) Concora may not be greatly affected by wet pressing if the increases in modulus are counterbalanced by the decreases in thickness, (2) dry pressing can reduce Concora because the reductions in thickness are not compensated by real increases in fiber-to-fiber bonding and (3) increasing the fiber orientation increases the elastic modulus and Concora in the m.d. direction. Brecht and Bachmayer proposed an empirical modification of Eq. (1) which related Concora to the modulus, basis weight, and the square of the thickness. The relationship explained the general trends but there was considerable scatter indicating other factors are involved.

There are theoretical and measurement difficulties in directly applying the frame analysis approach. Among the measurement factors are the determination of (1) effective caliper and (2) modulus after forming. Theoretical difficulties involve allowance for inelastic and/or shear affects, proper evaluation of end conditions, etc.

With these reservations, Fig. 32 shows preliminary frame equation estimates for medium sample 1 in comparison to flat crush and compressive strength. The frame loads are close to the flat crush magnitudes at reasonable frame heights - i.e., 0.060 to 0.075 inch (about 1.5-2.0 mm). They do not necessarily explain cold/hot flat crush differences because it is not possible at present to obtain Et values after forming.

The buckling coefficients in Fig. 32 were based on dimensions scaled from test photographs. There is an indication that hot-formed board has higher k^2 values than cold formed board. This would promote higher flat crush for the hot board.

It is believed the frame equations provide a conceptual way to explain the effects of variables such as flute geometry, medium thickness or weight, etc., on flat crush. However, to explain differences in flat crush due to forming conditions would require adjustment of either the geometrical or material properties in whatever theoretical approach is pursued.

In this connection 34 commercial mediums were fabricated into single-faced board on the Institute's experimental corrugator. Both cold and hot corrugating conditions were employed and the single-faced boards obtained at 600 FPM were evaluated for flat crush. The uncorrugated mediums were evaluated for a wide array of physical properties. The correlations between the uncorrugated medium properties and flat crush are summarized in Table III.

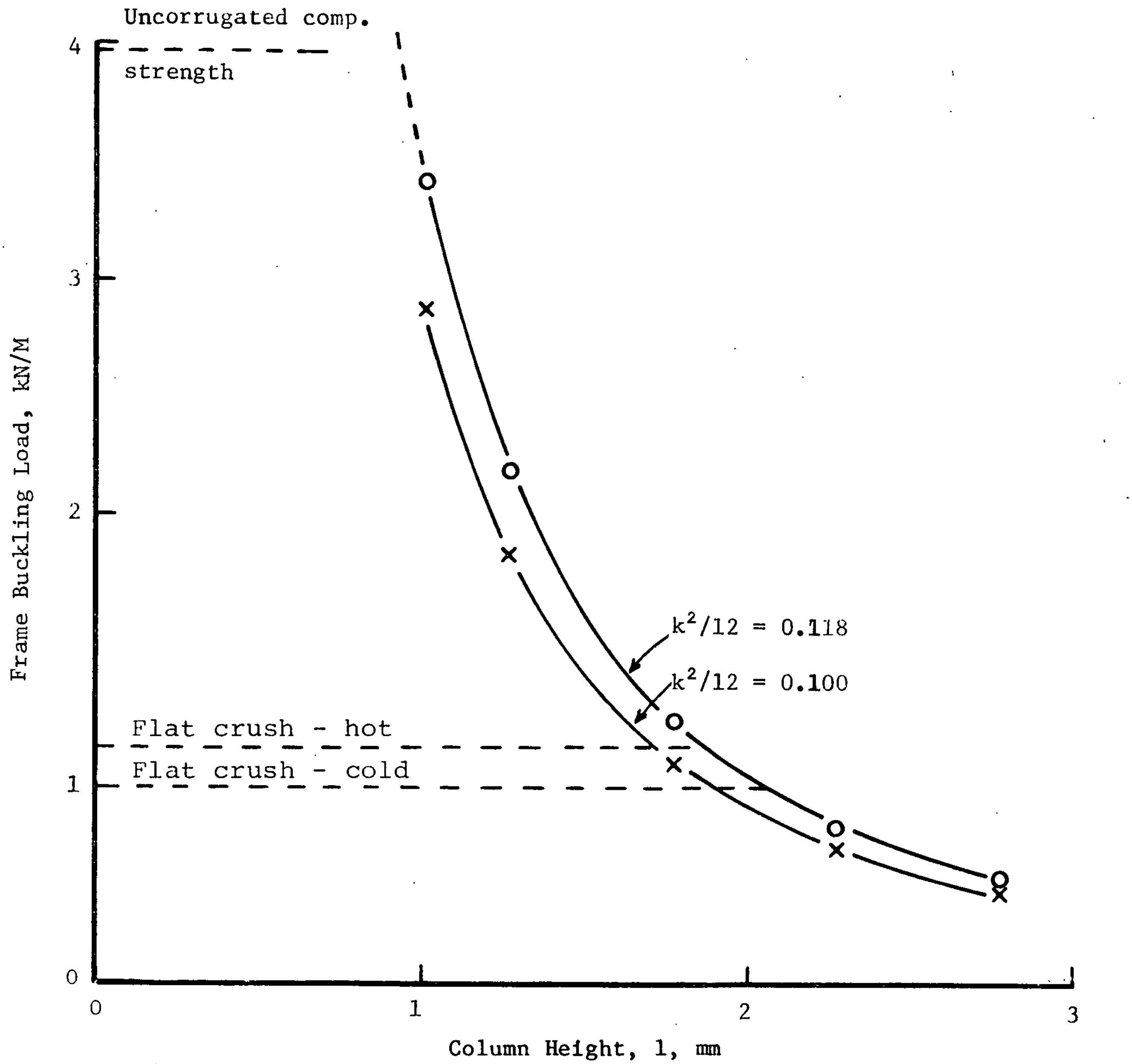

Figure 32. Frame Results for Various Column Heights at Constant Length to Width Ratios

TABLE III

FLAT CRUSH vs. VARIOUS MEDIUM PROPERTIES

- 34 MEDIUM SAMPLES -

Property	Correlation Coefficient	
	Hot Flat Crush	Cold Flat Crush (WTA)
Basis weight	0.21	0.34[a]
Caliper	0.07	0.12
Density	0.08	0.09
Moisture cont, cond.	0.19	0.25
Moisture cont, uncond.	0.03	0.19
Porosity	-0.25	-0.21
Smoothness	0.08	0.06
Friction, F.S. (cold)	0.11	0.46[b]
Friction, W.S. (cold)	0.18	0.49[b]
Concora	0.94[b]	0.60[b]
Mullen	0.42[a]	0.28
CD ring	0.59[b]	0.51[b]
MD tensile	0.60[b]	0.47[b]
MD stretch	0.32	0.16
MD TEA	0.46[b]	0.37[a]
MD Stretch	0.42[a]	0.41[a]

[a]Significant at 0.05 level.
[b]Significant at 0.01 level.

Under hot corrugating conditions the Concora results were highly correlated to flat crush as would be expected. However, the Concora correlation declined from 0.94 for hot corrugating to 0.60 for cold corrugating. Thus the Concora test which is based on a hot fluting action is well correlated to hot corrugating but not to cold corrugating.

Some of the other properties were correlated to flat crush but the correlations were not very strong.

CONCLUSIONS

Our research has focussed on several areas. They include the effects of hot and cold conditions on (1) fluted medium characteristics, (2) flute geometry, (3) flat crush load-deflection behavior and (4) the effect of various forming stresses on the compressive strength of the fluted medium.

Our results indicate that edgewise compressive strength and other properties of the medium are greatly reduced by the forming process. The reductions in medium strength are substantial and affect the quality of combined board made under either cold or hot corrugating conditions. The reductions in strength are caused by the high bending and tension stresses induced in the medium during forming. For some mediums the strength reductions are more severe under cold corrugating conditions and this reduces the ultimate flat crush strength. However, the initial flat crush load-deflection behavior is the same for both cold and hot forming, only the failure loads are different. Furthermore, the strength reductions caused by both forming processes are much more important as a subject for study than are the differences in strength between hot and cold formed structures.

More detailed conclusions are noted below.

(1) The edgewise compressive strength of the fluted medium is reduced in both m.d. and c.d. directions. The reductions range from 35-50% in the m.d. direction. The c.d. compressive strengths are reduced by about 20-30%. These findings are significant because they indicate that the fluting process degrades the compressive strength potentials of the medium in both directions. Thus box compressive strength, flat crush strength, and other combined board properties are all reduced.

(2) Some cold formed mediums show more evidence of compressive strength reduction in the flank/tip regions than under hot conditions. We believe this accounts

for the lower flat crush obtained with some cold formed mediums. It was also noted that such cold formed mediums tend to exhibit more compression degradation on the trailing flank than on the driven flank.

(3) The transverse bonding strength of the medium is also reduced by forming. The reductions in bonding would be expected to reduce the compressive strength and other properties of the formed medium.

(4) In simulation experiments, we observed that prestressing the medium in bending reduces edgewise compressive strength. Our results also show that the compressive losses are increased by higher tensions during bending. As expected, greater losses occur as the radius of bend decreases because the strain in the outer fiber layers is inversely related to the radius. These results suggest that the compressive strength losses - and hence the flat crush losses - are due primarily to bending stresses induced during forming.

(5) Analysis of clearances in the labyrinth shows that a potential pinch point exists about 1/2 flute ahead of the center line. In past work at the Institute, high speed motion photography shows that fracturing occurs before the medium reaches the centerline - also by about 1/2 flute. If the medium cannot freely slide past the "pinch point" it will be strained more highly and this will increase the risk of fracture or cause greater reductions in strength of the medium. Drives for both corrugating rolls (dual drives) have been tried at the Institute and elsewhere in the past to minimize clearance problems and improve fluting. However, in limited trials dual drives have not appeared to produce marked improvements in fluting performance.

(6) When the medium is formed around the flute tip the severe bending stresses are relieved by the simultaneous shear strains. Exploratory evaluations indicate the m.d. transverse shear modulus of medium is 30-40 times lower than the m.d. extensional modulus. Because of the low shear modulus, shear effects can be

an important factor in allowing the medium to conform to the fluted contour. Because the shear characteristics of the medium are important in corrugating, one aspect of future work should be the development of methods for evaluating and controlling this property. We would then be able to account for both bending and shear effects in corrugating and other forming operations in board conversion.

(7) A thorough review of flat crush technology was carried out. It appears that the initial portion of the flat crush load-deformation curve is critical in determining whether crushing in finishing will degrade board quality. However, the entire load curve is important because field performance depends on crush resistance up to ultimate failure.

Our observations indicate that cold and hot formed board exhibit about the same performance up to the first peak of the load-deformation curve. Thus cold and hot formed board should perform equally well in converting and end-use so long as the stresses are not materially greater than the initial peak load.

(8) Detailed analyses of hot and cold formed board indicate there are only small differences in profile shape. Thus, differences in the ultimate flat crush performance between hot and cold formed board are due to fluted medium characteristics rather than flute geometry.

(9) We also carried out a preliminary mechanics analysis of flat crush load-deflection behavior using finite element techniques. The finite element models appear to predict the general load response of the flute. The models also show promise of predicting the deflected shape as loading progresses. Among other things the initial results suggested that the shear characteristics of the medium may be of importance. However, the full power of finite element modeling cannot be brought to bear until we have completed development of methods of evaluating medium properties.

ACKNOWLEDGMENTS

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LITERATURE CITED

1. McKee, R. C. and Gander, S. W., Tappi 50(7):35-40A(July, 1967).

2. Gottsching, L. and Otto, W., Papier 30(10):417-25(October, 1976); 30(11):457-68 (1976); 31(2):45-53(February, 1977); 31(3):85-94(March, 1977); 31(4):129-36 (April, 1977); 31(5):169-79(May, 1973).

3. McKee, R. C., Tappi 43(3):218-28A(March, 1960).

4. Toroi, M. and Kolhonen, E., Pulp Paper Mag. Can. 77(10):T194-7(October, 1976).

5. McKee, R. C. and Gander, J. W., Project 1108-22, Report One to the FKBG. Feb. 29, 1960.

6. Thomas, C. E. 1979 Corrugated Containers Conference Proceedings. pp. 39-48.

7. McKee, R. C., Whitsitt, W. J., and Corbett, H. M., Pbd. Pkg. 58(12):44-6 (Dec., 1973).

8. Winegar, D., Pbd. Pkg. 63(7):64-8(July, 1978).

9. Fox, T. S., Whitsitt, W. J., and Becher, J., Project 2696-16, Report One to FKBI March 3, 1976.

10. Sprague, C. H. Cold Corrugating, Proc. of the Forty-Second Executives' Conference. p. 18-22.

11. Sprague, C. H. Cold Corrugating, Proc. of the Forty-First Executives' Conference. p. 106-13.

12. Wilson, H. W., Fibre Containers 44(4):69-72(April 1959).

13. Peters, W., Pbd. Pkg. 46(2):60-3(Feb. 1961).

14. Whitsitt, W. J., Laughlin, M. J., and McKee, R. C. Project 2696-8, Report Two to the FKBI, Oct. 18, 1972.

15. Nordman, L., Toroi, M., Papier-Kunststoff Verarb. 5(10):7-8, 10, 12, 14, 18(Oct., 1970); Boxboard Containers 78(4):94-8S(Nov. 1970).

16. McKenzie, A. W. and Yuritta, J. P., Appita 27(2):106-11(Sept., 1973).

17. Gartagonis, P. A. and Ostrowski, H. J., Tappi 51(10):471-81(Oct., 1968).

18. Sakakura, T., Hirakawa, T., and Littleton, R. 1979 Corrugated Conference Proceedings, pp. 65-69.

19. Fingerless Single-Facer Relieves High and Low Corrugation Problems. Boxboard Containers. April, 1979. pp. 46-7.

20. Situlman, J. J., Pbd. Pkg. 18(12):108-12(Dec. 1979).

21. The effect of crushing on the strength properties of corrugated fiberboard, Compression Report Two to the Fourdrinier Kraft Board Group, April 1, 1947.

22. Fatigue characteristics of corrugated board in flat crush, Compression Report Twelve to the Fourdrinier Kraft Board Group, May 1, 1949.

23. Staigle, V. H., Tappi 50(1):45-7A(Jan., 1967).

24. Crisp, C. T., Stott, R. A., and Tomlinson, J. C., Tappi 51(5):80-3A(May, 1968).

25. Nordman, L., Kolhonen, E., and Toroi, M., Pbd. Pkg. 63(10):48, 50, 52, 54, 56, 61-2(Oct. 1978).

26. Morris, R. J., Jr., Pbd. Pkg. 63(8):72-5(Aug. 1978).

27. Comparative evaluation of band C-flute boxes and combined board fabricated with various corrugating medium weights, Report Two, Project 2695-18, Feb. 7, 1977.

28. Cavlin, S. and Fellers, C., Svensk Papperstid. 9:329-32(1975).

29. Hardacker, K. W., Baum, G. A., and Fox, T. S., Project 2692-1 (3371-1), Report One to FKBG of API, Feb. 28, 1979.

30. Brecht, W. and Bachmayer, G. A., Wochbl. Papierfabr. 11/12:383-90(1968).

31. Stockman, V. E., Tappi 57(7):93-7(July, 1976).

32. Timoshenko, S. Theory of Elastic Stability. McGraw-Hill Book Co., Inc., New York, 1936.

THE INSTITUTE OF PAPER CHEMISTRY

W J Whitsitt

William J. Whitsitt
Research Associate
Containers Group
Paper Materials & Systems Division

Clyde H. Sprague

Clyde H. Sprague
Director
Paper Materials & Systems Division

APPENDIX I

MATERIALS AND PROCEDURES

MATERIALS

Four 26 lb (ca. 127 g/m^2) mediums were selected for evaluation in the main parts of the study as follows:

1. Roll No. 1, semichemical
2. Roll No. 10, semichemical
3. Roll No. 19, semichemical
4. Roll No. 114, recycled fiber

Sample rolls 10 and 114 exhibited comparable flat crush levels under both hot and cold corrugating conditions. Sample rolls 19 and 1 exhibited lower flat crush under cold conditions than under hot conditions.

CORRUGATING

Each roll was corrugated in the Institute's experimental corrugator under both hot and cold conditions. In the "hot" runs the corrugating rolls and preconditioner were maintained at 350°F and the steam showers were used.

In the cold runs the preconditioner and corrugating rolls were at room temperature. The mediums were treated on both sides prior to the labyrinth with a solid "slip" agent comprised of paraffin wax, graphite, stearin, and silicone oil.

In other studies with these mediums single-faced board samples were taken at speeds up to 600 FPM at minimum web tension. For this study additional samples of (1) the formed but unglued medium and (2) single-faced board were obtained at a speed of 200 FPM under both hot and cold conditions.

TEST PROCEDURE

The uncorrugated mediums were characterized in terms of a wide array of physical properties as shown in Table IV. The STFI compression test was developed at the Swedish Forest Products Laboratory by Cavlin and Fellers (28). The Weyerhaeuser lateral support apparatus was described by Stockman (31).

TABLE IV

PROPERTIES OF THE UNCORRUGATED MEDIUM

Property		Roll 10 Eng. Units	Roll 10 SI Units	Roll 114 Eng. Units	Roll 114 SI Units	Roll 19 Eng. Units	Roll 19 SI Units	Roll 1 Eng. Units	Roll 1 SI Units
Basis weight, lb/M ft^2 (g/m^2)		26.0	126	28.2	136	26.3	127	26.1	126
Caliper, mil (μm)		10.2	259	10.8	274	10.7	272	9.2	234
Density, lb/m ft^2-mil (kg/m^3)		2.55	486	2.61	496	2.46	467	2.84	538
Concora crush, lb, N (CMT)		52.2	232	66.7	297	63.7	283	76.8	342
Coeff. of friction[a]	73°F	--	0.58	--	0.52	--	0.54	--	0.54
	310°F	--	0.44	--	0.24	--	0.25	--	0.28
Edgewise compression, lb/in. (kN/m)									
STFI compression,	MD	18.9	3.31	22.5	3.94	20.9	3.66	23.3	4.08
	CD	11.6	2.03	12.1	2.11	13.4	2.34	12.2	2.14
Weyerhaeuser comp.[b],	MD	12.5	2.19	14.7	2.57	15.3	2.68	17.8	3.12
	CD	8.2	1.43	7.3	1.28	10.3	1.81	9.8	1.71
Tensile strength, lb/in. (kN/m)									
	MD	25.8	4.52	53.6	9.38	34.9	6.11	43.2	7.56
	CD	13.1	2.29	17.5	3.06	17.0	2.98	14.9	2.61
Ultimate strain, % Tensile	MD	0.94	--	1.42	--	1.22	--	1.04	--
	CD	1.30	--	4.24	--	1.79	--	2.57	--

TABLE IV (continued)

PROPERTIES OF THE UNCORRUGATED MEDIUM

Property		Roll 10 Eng. Units	Roll 10 SI Units	Roll 114 Eng. Units	Roll 114 SI Units	Roll 19 Eng. Units	Roll 19 SI Units	Roll 1 Eng. Units	Roll 1 SI Units
Compressive[b]	MD	0.41	--	0.37	--	0.45	--	0.42	--
	CD	0.59	--	0.58	--	0.59	--	0.67	--
Et stiffness, lb/in. (kN/m)									
Tensile,	MD	3770	660	6176	1080	4360	760	5410	950
	CD	1730	303	1791	313	2100	368	1810	317
Compressive[b]	MD	3440	602	4660	816	3920	687	4660	816
	CD	1740	304	1650	289	2050	359	1810	317
ZDT strength, psi (kPa)		64	440	62	430	69	480	85	590
VVP bonding[c], kp-cm/sec		--	614	--	680	--	548	--	450
Porosity (Bendtsen), ml/min		--	332	--	909	--	846	--	958
Smoothness (Bendtsen), ml/min									
	Felt side	--	2999	--	3126	--	2813	--	2548
	Wire side	--	2931	--	3171	--	2705	--	2663
Water drop, sec		--	27	--	36	--	554	--	86

[a]Kinetic friction between steel and medium surfaces.
[b]Weyerhaeuser lateral support apparatus and method.
[c]Determined using IPC bonding strength test (rupture endpoint).